TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

ARTEM VASSILYEV

INDOOR NAVIGATION ON SMARTPHONES

Master of Science Thesis

Examiners: Dr.Sc. Jussi Collin
Prof. Jarmo Takala
Examiners and topic approved approved in the Computing and Electrical Engineering Faculty Council meeting on 9th April 2014

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
Master’s Degree Programme in Information Technology
VASSILYEV, ARTEM: Indoor Navigation on Smartphones
Master of Science Thesis, 46 pages, 3 Appendix pages
November 2014
Major: Positioning and Navigation
Examiner: Dr.Sc. Jussi Collin, Prof. Jarmo Takala
Keywords: smartphones, indoor navigation, step detection, wireless technologies, android programming

Today the main issue of absolute navigation system mainly consists of GNSS signal propagation problems in indoor areas and street canyons (also known as urban canyons). The existing solutions are unable to provide reliable location service in these areas thus a new approach is needed. Due to the rapid growth of smartphone market, wireless transmission networks (e.g. Wi-Fi, Bluetooth, WiMAX) have been gaining popularity over the last few years. These types of networks were originally designed for high-speed transmission of large data i.e. Internet access, but it can also be used for the navigation purposes. Moreover, during the evolution of smartphones, manufacturers started to add new types of self-contained sensors that have never been used in such a way before. Some of them like accelerometers, magnetometers and gyroscopes can be used to track movement and position of smartphone in space.

During this research one of the latest and the most sensor-equipped smartphone was tested. Nexus 5, released by Google, was utilized as a testing platform for indoor tracking application based on self-contained sensors only. This implies a highly laborious and tedious work of manually collected training data and developing the corresponding indoor tracking application. The methods used in development process allows decreasing the overall development costs while notably improving the performance of the existing navigation systems.

The implemented indoor navigation application utilizes pedestrian dead reckoning method that allows improving the accuracy of existing navigation methods. It can also be used separately in fingerprinting or SLAM process. This application was tested in several indoor areas with different location properties: narrow corridors, wide halls, tiny rooms. The corresponding application utilizes built-in accelerometers, magnetometers and step detectors to track the route. Magnetometer fluctuations were smoothed by using low-pass filter. The experiments showed the total positioning error between 7% and 14%, respectively. Tests of built-in step detector showed the average detection error of 0.5%, which is lower than existed solution can obtain. In general, the obtained positing error and performance improvement can be considered as immaterial but the results can be used as a platform for the future research.

PREFACE

This work has been conducted at the Department of Pervasive Computing of Tampere University of Technology.

I would firstly thank my supervisors Jussi Collin and Jarmo Takala for their comments and guidance, for their continuous support and patience, for the encouragement throughout the course of this thesis work.

I also want to extend my gratitude to those people, who helped me to enjoy the moments of living in Tampere: my family, who always supported me, and my friends, with whom we spent the best time in my life.

Additionally. I would like to thank my mother for her love, care and patience during the last few years.

Дополнительно благодарю тех людей, кто так же помог мне в написании работы, а именно: мою семью, друзей, всех тех, кто был рядом со мной, помогал выжить в холодные, снежные ночи и морально поддерживал меня. Тезис так же посвящен ушедшим дням моей славной и беззаботной юности. Я всегда буду о вас помнить и ценить. Хочу так же выразить отдельную благодарность Александру Дименту за несколько прекрасных лет совместной жизни в одном общежитии. В завершении я хочу сказать спасибо Н.А. Назарбаеву за возможность свободно жить и учиться.

Artem Vassilyev
Tampere, September 2014

TABLE OF CONTENTS

TERMS AND ABBREVIATIONS

ADT	Android Development Tools
AIDC	Automatic Identification and Data Capture
AP	Access Point
API	Application Programming Interface
CDMA	Code Division Multiple Access
CDT	C++ Development Tools
ECEF	Earth Centred Earth Fixed
EKF	Extended Kalman Filter
FDMA	Frequency Division Multiple Access
GNSS	Global navigation system service
GPS	Global Positioning System
HPF	High-Pass Filter
IDE	Integrated Development Environment
IEEE	Institute of Electrical and Electronics Engineers
JDT	Java Development Tools
LPF	Low-Pass Filter
MB	MegaByte
PDR	Pedestrian Dead Reckoning
RAM	Random-Access Memory
RF	Radio Frequency
RFID	Radio Frequency Identification
RMS	Root Mean Square
RSS	Received Signal Strength
SLAM	Simultaneous Localization and Mapping
SV	Satellite Vehicle
TH-IR	Time-Hopping Impulse Radio
TOA	Time-Of-Arrival
UI	User Interface
UUID	Universally Unique IDentifier
UWB	Ultra-WideBand
Wi-Fi	WIreless-FIdelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

1. INTRODUCTION

1.1 Background

During the last few years the area of GNSS positioning has been changed greatly: new satellites were launched, new companies produced their own solutions and, finally, the system became fully operational and precise. Every modern smartphone has a function of position determination and navigation using GPS/GLONASS satellite system. Today, the accuracy of civilian GNSS navigation modules is close to a couple of meters which is more than enough for everyday usage. But the main issue of GNSS is an impossibility of the signal to go through the thick, concrete walls. In respect the fact that cities are growing fast today and the modern buildings are quite high, the problem of GNSS signal propagation becomes more and more relevant. In this thesis work indoor navigation system is presented as a way of solving this issue [27].

Indoor positioning can be considered as a branch of outdoor positioning since it uses the same methods and usually works as a complement of existing GNSS. The most popular and the easiest way to deploy the wireless positioning network is based on Wi-Fi positioning. The whole indoor area should be scanned and the map of the environment should be also built. Finally the maps should be shared between the users via existing wireless network and to provide the maximum coverage. Using of Wi-Fi in indoor navigation means that not only mobile phones will be available to determine its position but also laptops, tablets and even other Wi-Fi routers, as long as it has special software on-board. Certainly, Wi-Fi positioning has a set of issues that engineers should care about (issues are presented more detailed in Chapter 2). Indoor navigation system based only on Wi-Fi signals is very inaccurate and the result lying in a radius of 10-20 meters can be considered as very good. In this case many companies who are producing indoor navigation applications started to combine several methods and algorithms into one complicated solution. It is impossible to determine what company was the first who decided to use self-contained sensors, but today this technique is prevailed [9], [10].

The largest part of companies working in the area of indoor navigation is located in the United States. During the thesis work the author contacted with several research groups to study the state of industry and for deeper understanding of indoor navigation principles. During one of the interviews the company called Navizon agreed to provide beta version of indoor navigation software for testing and studying. After the test a feedback was sent to a company and the results were used in this thesis work.

1.2 Problem Definition

Today there are a lot of applications available in Play Market and AppStore that can be used for indoor navigation. All of them show a very precise positioning accuracy in case of intensive enough preparation. Some of these applications need to get a map of building; others may not provide good accuracy without initial fingerprinting, in both ways nothing will work just out of box. This makes indoor navigation area very specific, interesting for enthusiasts only. But this area is quite fresh and fast-growing, new solutions are coming almost every years and a lot of researchers are busy in this area. This makes the area very interesting in terms of applying of new methods and experimenting with new hardware.

Almost every new smartphone brings some innovation on the scene and sometimes indoor navigation companies do not react fast enough to use all the features available in a particular model. In October 2013 the new smartphone with two totally innovative sensor APIs (step counter and step detector) was released, but none of the software manufacturers have created an application that would use these sensors. Furthermore, there have neither tests nor comparison with other models or corresponding software analogues been done. Thus the potential of using this type of hardware sensors in not studied yet and the practical properties are unclear.

Since the accuracy issue is almost solved (in good environmental conditions), the large part of engineers are working on the scalability problem: there is no single database where every user can download/upload the map of a building since every company provides own unique standards for map creation. Thus even if methods are working brilliant, without a good coverage indoor navigation risks to stay just as a toy for geeks and researchers.

1.3 Objects and Main Results

The object of this thesis consists of analysing state-of-the-art, studying new techniques for indoor navigation, implementing and improving of existing methods as well. Furthermore, the overview of the existing indoor navigation software provided by Navizon Co. can be also considered as one of the priority goals.

The main result of the thesis is a developed Android application that uses new type of self-contained sensors called step detector and step counter. Results of the tests showed high accuracy of step detection, meaning that this type of sensors can be used in a real indoor navigation software. Moreover, the results of software tests provided by Navizon Co. showed that this type of sensors can be a good alternative for existing software implemented step detectors in terms of power consumption.

1.4 Thesis Outline

The core of this thesis is indoor navigation methods for smartphone. The thesis is organised as follows: Chapter 2 briefly shows the concepts of positioning methods in general, the history of navigation, existing techniques and perspective researches. In the last part of Chapter 2 to the essential ideas of the whole area are given.

Chapter 3 introduces methods that were utilised during this thesis work. Not only theory and software part are described here but also hardware overview is given. Several algorithms and code examples are also presented in the Chapter 3. Chapter 4 shows comparison results of two different step detection methods, also the results of indoor applications testing are given. Finally, several conclusions are presented in Chapter 5, suggestions for improvement and future research directions are also given in this chapter.

2. LITERATURE REVIEW

In the following, the basic terms of navigation will be introduced, the technologies that are necessary for indoor navigation will be discussed. The chapter concludes with the fundamentals of navigation. Firstly GNSS and WPS systems, as a part of the absolute navigation system, will be presented. Secondly, the overview of existing indoor navigation techniques will be given.

Then the discussion moves to the basics of simultaneous localization and mapping technique. Next the concept of emergency navigation services will be introduced. Finally the introduction to filtering theory will be given.

2.1 Pedestrian Navigation

Pedestrian navigation is a combination of different navigation techniques including GNSS, WLAN positioning, relative positioning and others designed for pedestrians. Moreover, pedestrian navigation provides not only the current position of user but also a lot of useful information like bus schedule, nearby shopping centres, weather forecast. At present, pedestrian navigation is less accurate than road navigation because it is usually impossible to get the strong GPS signal in the urban area.

Pedestrian navigation requires more complex maps and algorithms than road navigation since the environment is much more unpredictable. Pedestrians usually move near the buildings where the signal is shadowed, near the trees and in the indoor areas. For these indoor and urban areas two methods other than GNSS can be distinguished: absolute and relative positioning methods. Both of these methods will be considered in this chapter.

2.1.1 Absolute Positioning

Absolute positioning systems provide the current position of user in ECEF (Earth-Centred Earth Fixed) coordinates. Theoretically absolute positioning includes several different navigation types but in reality only GNSS is a pure solution. All the other systems provide the position in some frame: for example, in the certain building (e.g. Wi-Fi positioning). Most of the absolute positioning systems are based on transmitting the radiofrequency waves and measuring the time of arrival.

2.1.1.1 Global Navigation Satellite System

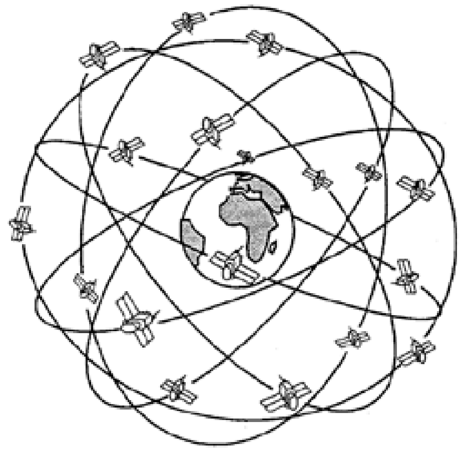


Figure 2.1. Satellite orbits

GNSS is the world's first absolute positioning system. It is based on 24 satellites rotating on 8 circular orbits around the Earth (Figure 2.1). This position model allows to acquire the full global coverage and very good accuracy. Several GNSS systems can be used together for better integrity. With the same purpose satellite-based positioning can be combined with cellular networks.

GNSS uses the concept of Time-Of-Arrival of signals combined with triangulation/trilateration to determine user's position. It needs at least 3 satellites to determine the user's coordinates x,y,z (horizontal, vertical, height) and the 4th satellite is needed to determine the time. In a general way, user's coordinates can be found using this equations:

$$d_i = c(t_{R_i} - t_T) \tag{2.1}$$

$$d_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \tag{2.2}$$

where t_{R_i} denotes the time when the signal from the i^{th} satellite reached the user, t_T denotes the transmitter time(it is the same for all the emitters), x y z are the user's coordinates and$x_i y_i z_i$ are the coordinates of the corresponding satellite. But since the signal from satellites is coming through the ionosphere and troposphere it can be refracted and rich the receiver with a delay. These are not the only error sources for GNSS signal; multipath errors, clock errors, reflections in suburban areas can be the reason of the error in final position. The most typical error sources and their typical range errors are presented in Table 2.1[37].

According to the fact that due to large amount of error sources the true range between satellite and receiver cannot be determined, the term of pseudorange was invented. Pseudorange is defined as a distance between SV (satellite vehicle) and receiver with the clock bias. But the measured pseudorange contains also several error sources like ionospheric and tropospheric delays. Measured pseudorange is thedistance between SV and receiver considering all the possible error sources (Equation 2.3.).

$$\rho_i = d_i + \varepsilon_{i1} + \varepsilon_{i2} + \varepsilon_{i3} \dots \quad (2.3)$$

where ρ_i is a pseudorange, ε_i is a corresponding error source.

Table 2.1. GNSS error sources

Error source	Typical range error
SV clock	1 m
SV ephemeris	1 m
Selective availability	10 m
Troposphere	1 m
Ionosphere	10 m
Pseudo-Range noise	1 m
Receiver noise	1 m
Multipath	0.5 m
RMS error	15 m

Presently, there are two GNSS systems that provides the global coverage: GPS and GLONASS. Both were originally made for military purposes and became operable for only in the middle of 1990s. The initial positioning estimation error of GPS reached hundreds of meters since the civilian signal was intentionally degraded in military purposes. It was improved only in 2000 when the civilian precision was rapidly changed to 20 meters. Today, modern GPS receivers can provide horizontal accuracy of less than 3 meters. On the other hand, despite the fact that GLONASS reached the full constellation in 1995, it became available as a genuine GNSS for civilians after 2011 since the largest part of satellites were lost during the crisis of 1990s. The main difference between GLONASS and GPS is the signal structure: GPS signal is based on CDMA while GLONASS is based on FDMA. But since 2008 GLONASS provides the ranging signal also in CDMA.

Both GNSS systems are using the same architecture based on three segments: space segment, control segment and user segment (Figure 2.2).

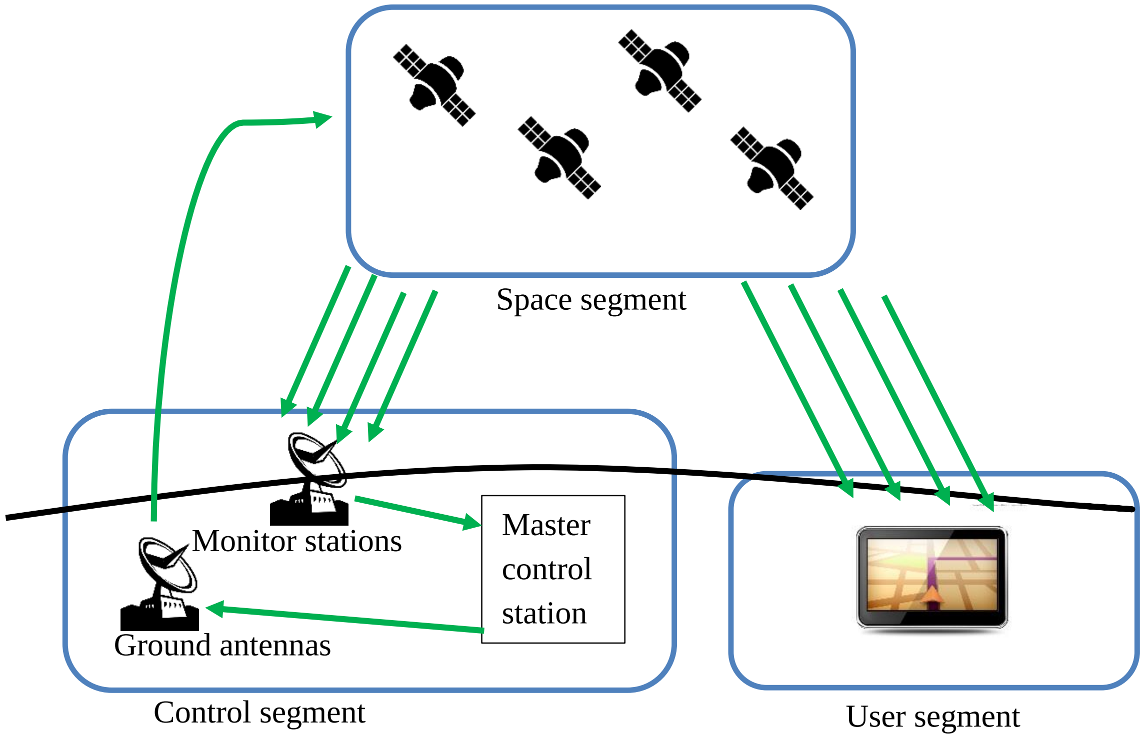


Figure 2.2. Three GNSS segments

Space segment generates and sends ranging signals. It is the most important GNSS segment since it is responsible for accurate positioning. It consists of satellite constellation where all the satellites are synchronized in time. Orbital periods and speeds are calculated using the relations [38]:

$$4\pi^2 R^3 = T^2 GM \tag{2.4}$$

$$V^2 R = GM \tag{2.5}$$

where R denotes the radius of orbit in metres, T denotes orbital period in seconds, V denotes orbital speed in m/s, $G \approx 6.673\times10-11$ Nm²/kg², $M \approx 5.98\times1024$ kg.

Control segment consists of master control station, ground antennas and monitor stations. The main functions are satellite monitoring and maintaining, GPS time correction and navigation message updating. There is usually one control station and several monitor stations combined with ground antennas located in different parts of the planet.

User segment consists of the GPS/GLONASS receivers and the user community. Receiver converts SV values into user's position, velocity and time using triangulation principle: the position is found on the intersection of satellite radiuses as it shown on the Figure 2.3. The topic of the thesis is mainly focused on the user segment since the smartphone can get the position from GNSS and use it as initial point of indoor positioning.

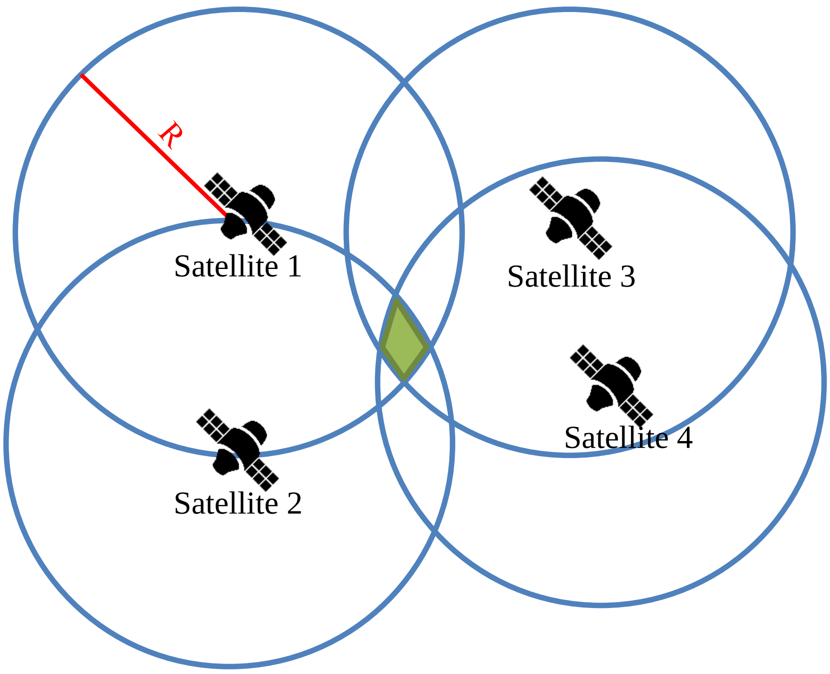


Figure 2.3. Satellite trilateration

2.1.1.2 WLAN Positioning

Wireless Local Area Network (WLAN) is a wireless network used to connect different kinds of electronic devices. It is based on 802.11 standards and operates in 2.4 and 5 GHz bands with maximum data transfer rate of 600 Mbit/s. Client communicate indirectly through the access point which is usually a bridge between radio and wired network. Since access points are connected to electrical network permanently, they are usually equipped with high-powered transmitters.

WLAN based positioning or WPS is also based on triangulation but unlike GNSS it uses Wi-Fi routers instead of satellites. The main issue is a scalability: due to the large amount of the transmission devices and their uncontrolled mobility, the idea of making the unified Wi-Fi router database turns to almost impossible. Thus every company working in the area of indoor location

WPS can offer a complementary solution to GPS indoor and urban areas: WLAN infrastructure is already exists and the coverage is very high especially in big cities, it is already standardized (802.11k and 802.11v standards). The standards declare the adding of position data to a data transmission packet. Access points can query each other's position and provide their location and the list of nearby access points to user. Users are allowed to exchange the information about the network topology [22].

WLAN positioning methods can be divided into two classes: Timing-based and Received Signal Strength (RSS)-based. In recent times RSS-based positioning is dominating since it is easier to implement and does not need time synchronization. Moreover, Timing-based solutions require installing an additional hardware. Despite on the fact that RSS-based positioning is more widespread, it still has a very important issue: due to the uncontrolled mobility, it needs fingerprints to be collected continuously [19].

Fingerprinting is based on a set of RSS measurements taken of a target from multiple access points and comparison of the results with a previously compiled database. This method has several advantages:

- No time synchronization is required.
- The reading of RSS is inherent to the IEEE 802.11 protocol, and no special hardware is needed.
- Tags or devices based on the IEEE 802.11 standard can be tracked.
- The method is particularly applicable to indoor networks as the vagaries of multipath propagation are automatically accounted for in the reference database.

On the negative side, the method implies creating a database for the area to be covered, and changes in AP deployment and physical features of the environment require updating the database. The method is computationally intensive and a special location server is required for position outputs [27].

On the other hand there is a technique called SLAM that can substitute fingerprinting (Section 2.1.3). The main benefit of using SLAM lies in the fact that it creates map of measurements automatically while doing localization. Today a lot of companies are using SLAM instead of fingerprinting since it shows better performance in an unstable environment.

2.1.1.3 Bluetooth Positioning

Bluetooth aims at so-called ad-hoc piconets – local area network with a very low coverage and without a need of infrastructure. It represents a single-chip technology with very low energy consumption and based on wireless network technology. Bluetooth technology is limited to connect of maximum 7 users to one point that makes it inflexible. There is a good extension of Bluetooth standard called Wibree. This Ultra Low Power Bluetooth was released by Nokia in October 2006 and it is more power efficient but smaller range [3].

Bluetooth Positioning works the same as WLAN positioning but it has both advantages and disadvantages. Low power consumption allows to keep battery up to several years and the small size allows to mount it on any surface. But due to a lower than Wi-Fi range it needs more base stations to cover an area. The usual size of Bluetooth beacon is about 5 cm (the white one on the Figure 2.2) but there are very small solutions like beacons produced by StickNFind Co. StickNFind beacons are the size of at just 24mm in diameter and 4mm thick (the black one on the Figure 2.4.).

Figure 2.4. Different beacon types [26]

Bluetooth beacons costs much less than Wi-Fi access points but their functions are quite straight forward, while regular Wi-Fi access points can provide both positioning information and internet connection in the area. Furthermore, since Bluetooth beacons do not provide an Internet connection, user need some external Internet access to download indoor maps.

Today Bluetooth beacons a getting more and more popularity. Apple inc. was the first company who started to work in this area. The beacons produced by Apple are called iBeacons, it uses Bluetooth Low Energy technology that transmits three parameters: proximity UUID, major and minor. The range of 45 meters is announced. A *proximity UUID* (universally unique identifier) is a 128-bit value that uniquely identifies one or more beacons as a certain type or from a certain organization. A *major* value is a 16-bit unsigned integer that can be used to group related beacons that have the same proximity UUID. A *minor* value is a 16-bit unsigned integer that differentiates beacons with the same proximity UUID and major value. [24]

These beacons were installed in all the Apple stores in the United States in the end of 2013. The accuracy of iBeacon is between 1-3 meters with a clear line of site from a device to the beacon. [25] The beacons can be used in any indoor area, like city mall, not only for navigation purposes, but also for sending information messages, advertisements and warning messages. iOS devices can also be used as a beacon in iBeacon piconet which further extends the use of Apple devices and gain the popularity for iBeacon–compatible Bluetooth ad-hoc networks.

2.1.1.4 Radio Frequency Identification

Radio frequency identification (RFID) is part of the family of Automatic Identification and Data Capture (AIDC) technologies that includes 1D and 2D bar codes. RFID uses an electronic chip (transponder), usually applied to a substrate to form a label, that’s affixed to a product, case, pallet or other package. The information it contains may be read, rewritten and/or recorded [11].

Although the system was developed mainly for identifying the object, it can also be used for position determination. This method is based on tagging and called RFID positioning. The main idea is to attach users with special tags that can be observed with reader and equip base stations with radar. This technology is now used in supermarkets to track the movement of goods and prevent thefts, in fleet monitoring systems to extend GPS-based solutions.

2.1.1.5 Magnetic Field Positioning

Magnetic field positioning is one of the most rarely used methods of indoor positioning system. It is based on the fact that every building consist of unique combinations of steel and concrete constructions and constitutes the unique ambient magnetic field. By measuring magnetic field levels in different parts of the building, the user can estimate his position quite precisely if the area conditions are stable enough.

The largest issue of this method is to keep track on all the electronic devices that can effect on the state of magnetic field e.g. PCs, huge electrical devices, some specific RF devices; since every small change in the magnetic field can sharply increase the total positioning error.

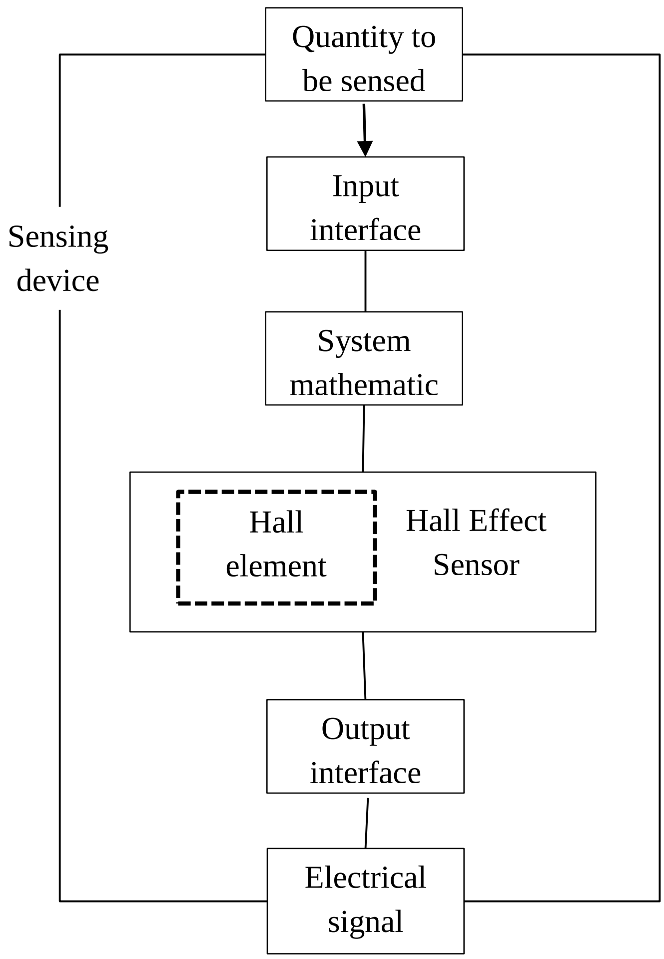


Figure 2.5. General sensor based on the Hall effect

The most part of magnetic field sensors that are used to be installed in smartphones are based on Hall Effect sensing (Figure 2.5.). This is well-known effect that was firstly used in 1950s as a microwave power sensor. The main features of Hall based sensors are:

- True solid state
- Long life (30 billion operations in a continuing keyboard module test program)
- High speed operation - over 100 kHz possible
- Operates with stationary input (zero speed)
- No moving parts
- Logic compatible input and output
- Broad temperature range (-40 to +150°C)
- Highly repeatable operation

One of the most successful companies using this method is “IndoorAtlas” - company is based in Oulu and provides interfaces, support and engage for a 3 meters [40] accuracy in the buildings with good magnetic field information.

2.1.1.6 UWB Positioning

Ultra-Wideband is a kind of High-rate WPAN. In general UWB systems are defined as systems with large absolute and relative bandwidth. Besides the large bandwidth, UWB communication systems have an advantage of information transfer speed, signal robustness, implementation simplicity. But it also leads to differences from standard, narrowband, systems.

The interest in UWB navigation systems is mainly due to the fact that an UWB system can be deployed in parallel to existing narrowband systems (as Wi-Fi or iBeacons), since it does not require any new spectrum. This fact can be clearly seen on the Figure 2.6.: transmit power of the system is defined as the product of power spectral density and bandwidth. Thus the low bandwidth allows UWB system to show the very low power spectral density. An ordinary narrowband receiver will only see the spectral noise inside its own bandwidth. This fact shows that interference between narrowband and Ultra-Wideband systems is very low [28].

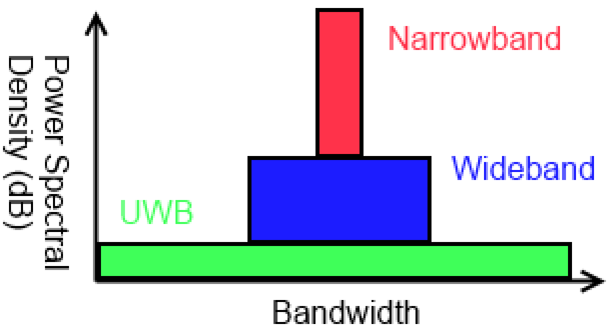


Figure 2.6. Power Spectral Density for UWB

Although the UWB provides extremely high data rates (over 100Mbits/s), the transmission can be achieved on a distances smaller than 10 meters. On the other hand, in the areas where the data rate is not as important as an operating range, larger distance can be obtained by exploiting the large spreading factor in low-rate-communications.

The benefit of using UWB in indoor navigation is an ability to penetrate many building materials as concrete, wood and ceramics. UWB can be performed both the same as an RFID (using RSSI method) or, similar to GNSS, measuring the Time of Arrival. It can also be performed without equipping user with special devices: UWB transmitter can work as a radar and measure the time of signal propagation and reflecting [28].

One of the most important application area of UWB is emergency communications e.g. between the rescue workers or people who were blocked or collapsed inside of the building. IEEE establish a standard IEEE 802.15.4.a that is based on TH-IR and enables very accurate geolocation on the transceivers [29].

2.1.2 Relative Positioning

In general, all the positioning is relative since it is related to some initial point. Even GNSS can be considered as a relative positioning system since a user's position is always computed relative to satellite coordinates, which can be assumed as absolute.

In this thesis, the position of user is mainly computed relative to its position at the previous point in time. This method is useful when the motion of user is more important than its absolute position.

This section presents the main purposes of self-contained sensors and principles of work. Relative positioning cannot be considered without absolute positioning since relative positioning needs an initial point. Relative positioning techniques such as dead reckoning are already used for several thousands of years since the first voyagers started to go to the ocean. They logged all the data that they could obtain from their primitive devices, such as the speed of wind, speed of the sea current, ship heading, and calculated the current position of a ship based on these measurements. Currently, all the relative navigation devices do the same but use more efficient algorithms and data analysis. Inertial navigation is used in a wide range of applications: navigation of spacecraft, submarines and ships, tactical and strategic missiles. The very important issue of relative positioning is an accumulative error which is very difficult to solve.

2.1.2.1 Inertial Navigation

Accelerometers and gyroscopes are called inertial sensors. The basic idea of all inertial navigation system is to integrate measurements from gyroscopes to get the attitude and to integrate twice the measurements from accelerometer to estimate the translation (Figure 2.7). The algorithm and the main principles of strapdown inertial navigation system

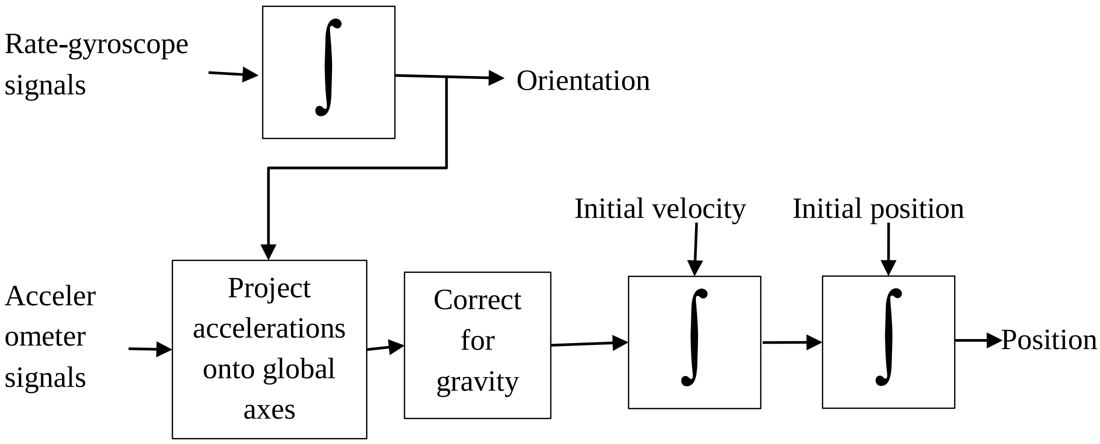


Figure 2.7. Strapdown inertial navigation algorithm.

can be found in [13]. Systems based on inertial sensors avoid line of sight issues, but their measurements are not absolute and are subject to error accumulation [1], [23].

The very important issue for pedestrian navigation is the size of equipment. Comparing to vehicle navigation where the size and weight of hardware is almost unlimited, pedestrian navigation solution should be very light-weighted, handy and usable. One of the greatest advantage of using inertial sensors in navigation is their ability to communicate with electrical elements in semiconductor chips. Other advantages are small size, low power consumption, low cost and high precision. [13].

2.1.2.2 Pedestrian Dead Reckoning

Pedestrian Dead Reckoning (PDR) is an estimation of user's relative position by analysing step counts and changes in heading. PDR works like an accumulator: knowing the initial point and getting the movement direction and speed the position of pedestrian can be determined.

The basic components that make an effect on the total PDR accuracy are: sensor calibrating, step detection, azimuth or heading estimation, detecting the phone's yaw, pitch and raw during the movement [5].

People usually do not hold their devised directly in front of them. They keep it in a pocket, handbag, holding the phone to their ear. PDR system should effectively recognise all the possible cases and make logical decision. So the key to a successful PDR is not only the sensor accuracy but also the logical chains. PDR algorithm should exactly determine if a person just walking straight or running or moving in elevator [4].

The whole PDR process can be divided onto three parts: step detection, step length estimation and position update by combining the heading obtained from magnetometer (or gyroscope combined with magnetometer) and a step length.

Step detection is usually based on accelerometer measurements. Since human's walk is not continues and every person got his personal walking style, the step can be easily

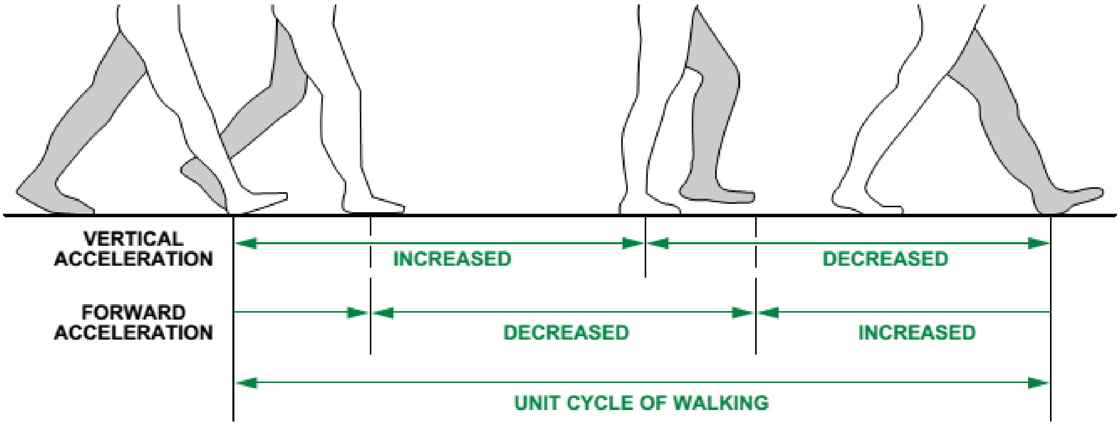


Figure 2.8. Walking stages and acceleration patterns [30]

obtained from the accelerometer data. Figure 2.8 shows the relationship between each stage of one step cycle and changes in forward and vertical acceleration.

In Figure 2.9, a typical pattern corresponding to vertical, forward and side acceleration is shown. The graphs are usually quite noisy so the digital filter is needed to smooth this signal. The basic filtering techniques are shown in the Section 2.3.

No matter how user is keeping the device – one of the axis will show periodical acceleration changes that are used to obtain the step happening. Thus the essential idea of step detection is to make a robust peak detection algorithm and dynamic threshold decision algorithm. In this thesis, the algorithm was already implemented in smartphone but understanding of the main principles of work is very important for application development.

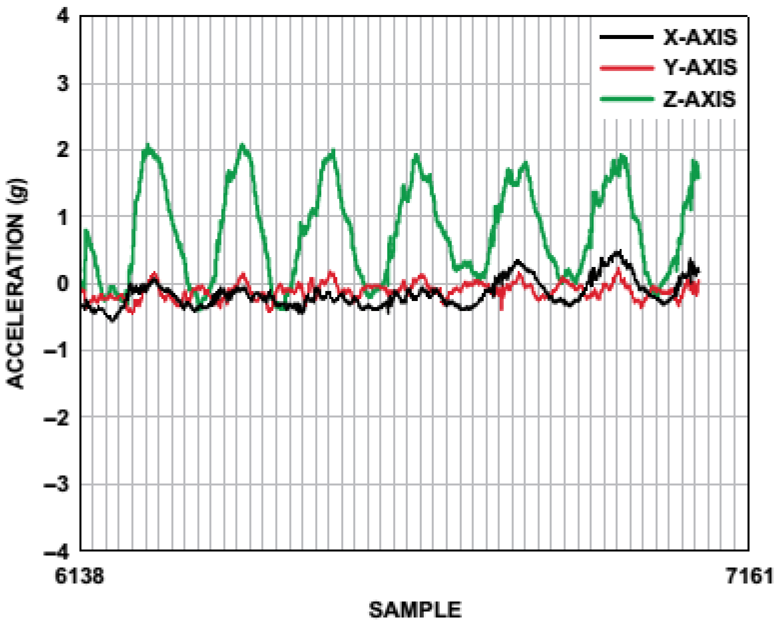


Figure 2.9. Typical pattern of x-, y-, and z accelerations measured on a running individual [30].

Step length can be obtained quite precisely, if the user's height is known, from the equation 2.6 [39]:

$$l = \frac{h}{4} + 0.37 \tag{2.6}$$

where *l* is a step length and *h* is the height in meters.

The third part is a *position update* is mainly based on computing the next position on the map using step length and heading. The distance between two points on the map can be found using the haversine formula:

$$d = 2r\, sin^{-1}\left(\sqrt{sin^2\left(\frac{\phi_2-\phi_1}{2}\right) + cos(\phi_1)\, cos(\phi_2)\, sin^2\left(\frac{\lambda_2-\lambda_1}{2}\right)}\right) \tag{2.7}$$

where *d* is the distance between the two points in kilometres; *r* is the radius of the Earth in kilometres; ϕ_2, ϕ_1 denote latitude of point 1 and latitude of point 2; λ_2, λ_1 denote longitude of point 1 and longitude of point 2. Using the equation 2.7 ϕ_2 and λ_2 can be found as:

$$\phi_2 = \sin^{-1}\left(\left(\sin\phi_1 \cos\left(\frac{d}{r}\right)\right) + \left(\cos\phi_1 \sin\left(\frac{d}{r}\right)\cos\alpha\right)\right) \tag{2.8}$$

$$\lambda_2 = \lambda_1 + \tan^{-1}\left(\frac{\cos\left(\frac{d}{r}\right) - \sin\phi_1 * \sin\phi_2}{\sin\alpha \sin\left(\frac{d}{r}\right)\cos\phi_1}\right) \tag{2.9}$$

where α denotes the heading in radians.

But the interest in PDR stems mainly from possibility of combining PDR systems with GNSS to provide the full coverage. Although PDR shows fairly good results, it still suffers from various errors, such as accelerometers and gyroscope errors (e.g. scale factor, noise, bias). Furthermore, low-cost accelerometers that are usually used in smartphones are subjected to stochastic errors such as thermal noise and drift [30].

2.1.3 Simultaneous Localization and Mapping

Simultaneous Localisation and Mapping (SLAM) is commonly defined as a method which allows robot or any other electronic device to get oriented in unknown location by building a map of environment and computing its own location in the same time [14]. From the end 1980s the problem of SLAM became one of the most important among the robotics community since computational power of electronic devices was not enough to process data in a real time. But these days it can be considered as solved [30]. The most important benefit of using SLAM is that device does not need any prior knowledge about its location. For instance, the most popular technique in Wi-Fi indoor positioning is fingerprinting, as it is easy to implement and quite precise. But in this

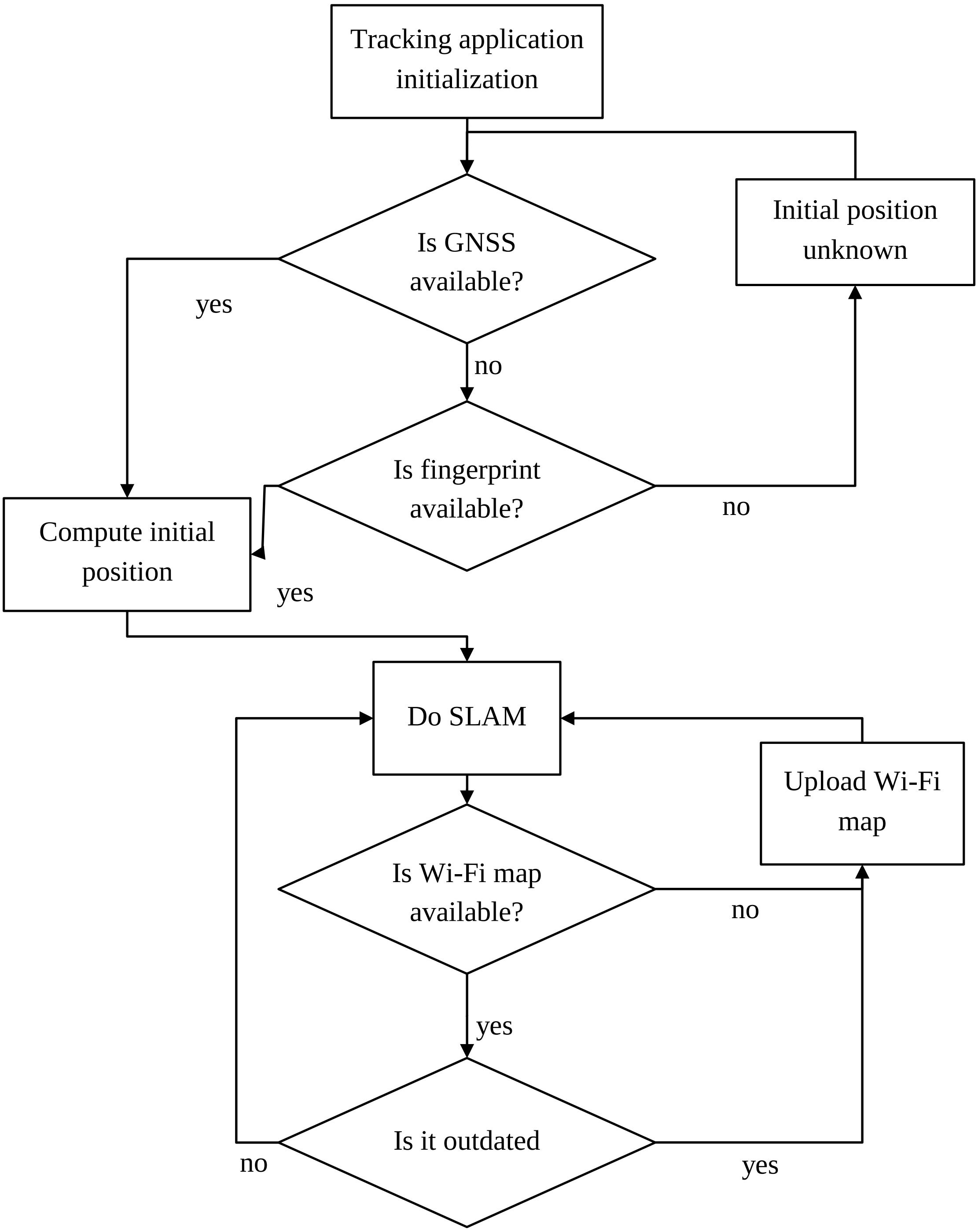


Figure 2.10. SLAM application process for smartphone

case fingerprints should be collected continuously to provide up-to-date information about the environment [31]. Using SLAM on smartphones allows to avoid continuous fingerprinting since every single smartphone can build own copy of environmental map and share it with other devices via special service shown on Figure 2.10. On the other hand Figure 2.11 shows SLAM from the server point of view with initial fingerprinting and some “threshold” - the number of received maps from different sources enough large to make a decision: what changes should be done in order to keep the map updated. The “filtering” stage means comparing maps received from several devices, reject

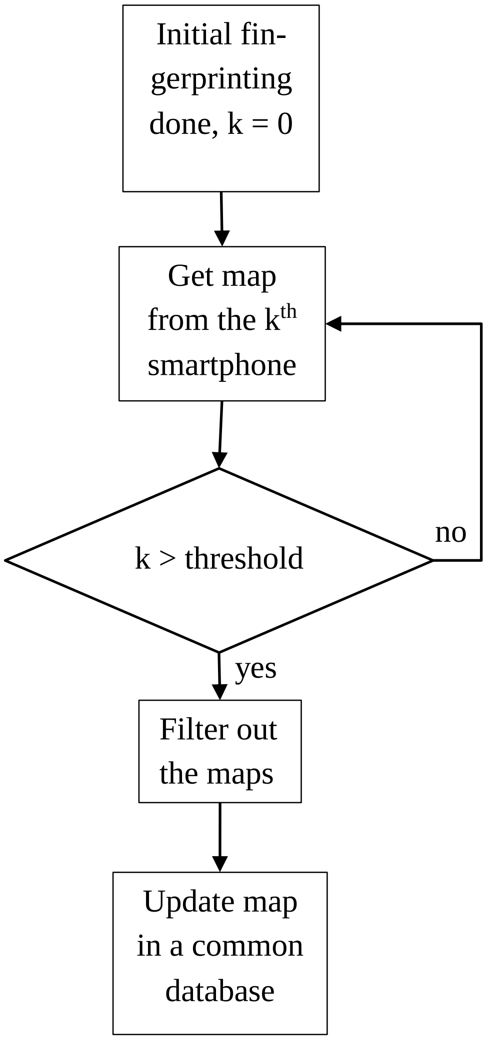


Figure 2.11. SLAM process for server side

ing the similar ones and computing the most probable current map of the area based on maps that were not filtered out. The issue of this method is the necessity to have a large enough amount of users to keep the map updated.

SLAM can be also implemented without any initial fingerprinting. In this case SLAM is based on self-contained sensors that the smartphone is equipped with. It uses accelerometers, gyroscopes, magnetometer and barometer to build a path in the building. But such systems are suffering from accumulative error thus it should be corrected by other absolute positioning system as GPS. It does not need any prior knowledge of a building or initial fingerprint, it can build the map itself and add it to a common database.

There are several different SLAM methods, the difference between them is a filtering methods that they use: EKF SLAM is based on extended Kalman filtering, Fast Slam utilizes Particle filter, CAT-SLAM is based on trajectory-based particle filter [31], [32], [36].

2.2 Filtering

In the last few years, data filtering was firmly enrooted in all the areas of science and technology. For instance, digital filters are uses almost in every area related to signal processing: spectral analysis, digital image/video processing. The goal of filtering is to pass the data that corresponds to the certain criteria and block the data that does not.

Any measuring device has got an observational error since it suffers from various noise sources both internal and external. As a result, the information on the output can be very noisy, inaccurate and very difficult for handling.

There are two different types of filters existed: digital filters and analogue filters. Digital filter is a system that processes digital (discrete) signal and reduce or enhance some aspects of the signal. Analogue filters work with analogue (continuous) signals such as voltage, sound or mechanical movement. Nowadays digital filters are used in the most applications but there are some areas where the analogue filters cannot be replaced.

Filtering also plays the key role in the process of positioning, especially in the indoor areas. No matter what method of positioning is used – there always exists the noise source: Indoor navigation systems are always deployed in the locations with high people density: airports, big city malls, sport centres. Thus there are several electronic devices that can interfere with each other decreasing positioning accuracy. Since the smartphone operates mainly with digital data, it should use digital filtering. There are a lot of different filters and filtering systems available today but in this section the filters that are mostly used in indoor positioning are introduced.

2.2.1 Highpass and Lowpass Filters

Highpass filter (HPF) is a type of digital filters that effectively passes signal spectrum with frequency higher than some threshold (cut-off frequency) and attenuates signal lower than this frequency. There are various implementations of HPF: electronic circuits, algorithms in programming languages, acoustical barriers and others. Figure 2.12 shows how the high-pass filter attenuates signal lower than 2 kHz. In this implementation filter does not cut the signal off but sharply reduce it.

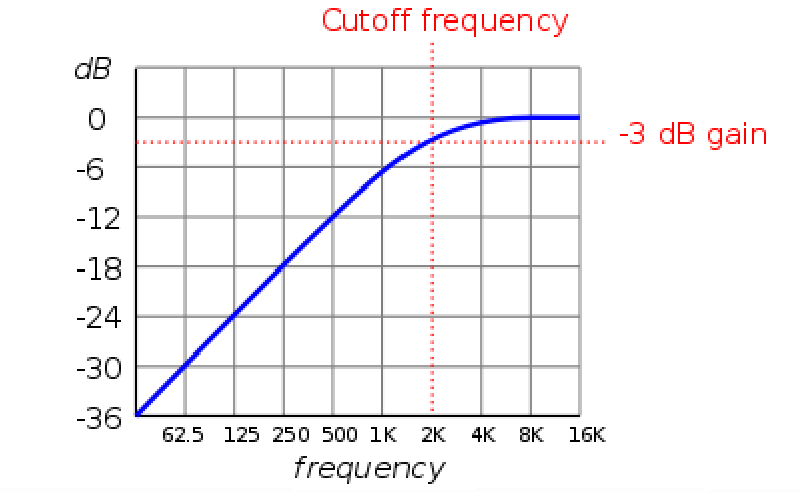


Figure 2.12. High-Pass Filter

Lowpass filter (LPF) is filter opposite to HPF – it attenuates signals that are higher than cut-off frequency and passes the signals of lower frequency. In this thesis low-pass filter was applied to attenuate magnetic compass fluctuations i.e. to smooth the data to get more accurate measurements (Chapter 2.2.). Ideal LPF totally attenuates all the frequencies higher than cut-off but such a filter can be implemented only in theory as multiplication of incoming signal and rectangular function [34].

2.2.2 Kalman Filter

Kalman filter is one of the most important filtering algorithms using in many areas of science and technology. Due to its efficiency and implementation simplicity it can be found in GPS-receivers, 3D modelling tools, radars, autopilots. Kalman filter is a kind of recursive filter. It means that the result of previous filter iteration and current estimations are needed to compute current system state. Based on the priori information about the system and dependences of the variables, it allows to predict the state of the system on the next step. It can also be used without priori information and the results will be still appropriate [12].

Kalman filter is based on dynamic system model (physical law of movement in this thesis). It uses the model to get an estimation that can be changed during the measurements. In order to control dynamical system effectively, the state of model in every particular moment should be known. Sometimes it is impossible to make a precise measurement of all the variables that should be controlled, and in this case Kalman filtering allows to restore missing values using deviated or noisy data [33].

Filter works in a prediction-update process (Figure 2.13.). Assume that on the timestep t_{k-1} the state of the system $\hat{x}_{k-1}$ was estimated and now it is needed to get an estimation in the moment t_k. For this purpose, prediction of $\hat{x}_k^-$ based on $\hat{x}_{k-1}$ is done, next, the values of Z_k are computed and the estimation in the moment t_k is corrected.

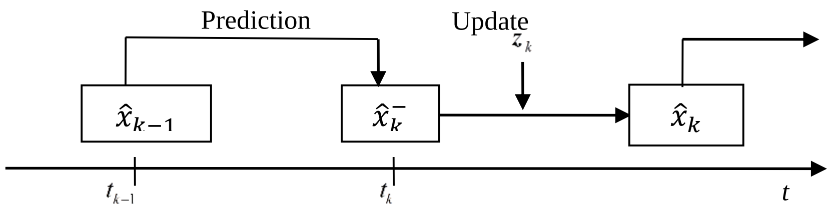


Figure 2.13. The main principle of Kalman filtering

Finally, the value of $\hat{x}_k$ is obtained based on prediction and measurements. $\hat{x}_k$ denotes *a posteriori* state estimate and $\hat{x}_k^-$ denotes *a priori* prediction. The algorithm is presented more circumstantially in Figure 2.14.

One of the most important problem of using Kalman filter is the fact that either the system model or the measurements model are not perfect.

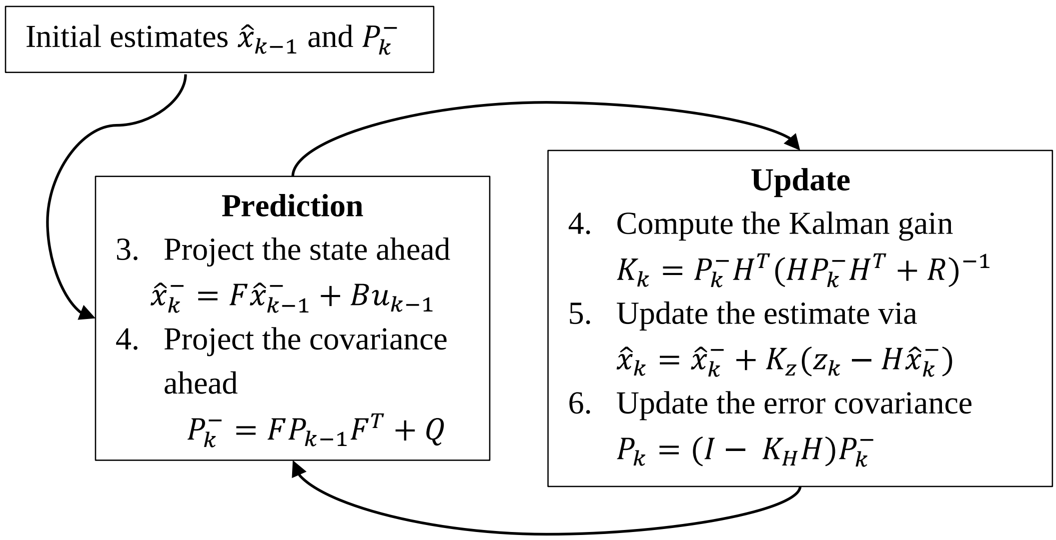


Figure 2.14. Kalman filter

$\hat{x}_k^-$ is a system state prediction in the current moment of time;
$\hat{x}_{k-1}^-$ is a state of the system in the previous moment of time;
P_k^- is a prediction of error;
P_{k-1} is an error in the previous moment of time;
u_{k-1} is a control vector in the previous moment of time;
Q is a noise covariance matrix;
F is a state transition model;
B is a control-input model;
K_k is a Kalman gain;
H is an observation model;
R is a covariance of the observation noise;
z_k is a measurement of a true state $\hat{x}_k^-$ at time *k*.

Statistical qualities of noise, specifically its covariance matrices, are the parameters that makes a great influence on the system state estimation accuracy i.e. on the filter accuracy in general. For this purpose adaptive filtering method can be used: the main idea of this method is simultaneous system state estimation and estimation of statistic characteristics of the noise. These characteristics are used to make changes in noise covariance matrix. In this case, the method of Covariance Tracking using Model Update Based on Lie Algebra [34] can be used.

2.3 Particular Qualities of Indoor Navigation in Emergency Situations

Today a lot of companies that are busy in indoor positioning are doing their research by request of emergency services. According to official statistics, the largest part of causalities between firefighters happens due to disorientation in the building full of smoke and fire. On 11 September 2001, 412 firefighters and other emergency responders died in the aftermath of the attacks on the World Trade Center, in New York City. One of the main reasons of such a huge causalities were technical difficulties with malfunctioning radio repeater systems that should provide information about current state of the scene and locate firefighter itself inside the building [35].

The story above shows the importance of the reliable indoor navigation system in case of emergency situations. The ability to locate the emergency workers became the important task for positioning engineers. In general, GPS system works fine and provides the perfect signal all over the planet but only for outdoor area. Inside the huge buildings with thick concrete walls any GPS navigator with any software and hardware becomes a useless piece of plastic. The range of 1100-1600MHz is too high to go through the walls without reflection and fading. The latest researches show that the range of 170-200 kHz perfectly fits for indoor positioning. These very low frequencies penetrate metal and concrete much more easily than do the high-frequency signals that outdoor tracking systems use. Combining these low frequency career signals with other kinds of tracking solutions like gyroscopes, accelerometers and magnetic field sensors can give outstanding results.

Another goal is to make the indoor solution as cheap as possible: today lots of companies provide working solutions for firefighters but the price for one item begins from 3000$ in average. Without any doubt this price is nothing comparing with the life of emergency workers but not all the emergency services, especially located in small towns, can afford to buy the devices that summary cost is equivalent to a cost of a fire truck [21].

But most of the solutions that are ready to use now are very weak in case of lack Wi-Fi signals which is decisive factor for emergency services. The basic scenario of emergency situation assumes a total disability of any electrical devices including Wi-Fi routers due to the emergency power outage. Thus the most important requirement for solutions intended to help people in different kinds of emergency is Wi-Fi/GPS independence, meaning that all the calculations of current position must be done using self-contained sensors only. One of the most successful solutions in this field was done using particle filtering with map-matching [14], [15], and [16]. Another solution is given in [17], "the backtrack" method is capable to go back in time in case of dead end of room is found. But due to peculiarities of particle filter implementation it is not available for using online. In some cases the typical smartphone can be used if it has built-in self-contained sensors that can be used for PDR methods described in section 2.1.2.2 All the listed algorithms are using a map of environment to reduce position drift.

2.4 Summary

Currently, the point of balance in both navigation software and hardware is reached: the development instrumentation is flexible enough and theoretical base is strong enough to produce a fully-function indoor navigation solution. Several companies are now competing between them to get the best, the most reliable and the easiest solution. The most prevailing technique is fingerprinting due to the easiest implementation and Wi-Fi access points availability, but new positioning methods as SLAM are also gaining the popularity.

Despite of all the successes there are still several problems left: fingerprinting in large areas, self-contained sensor's accumulative error, large variety of different smartphone models with different hardware on board that can cause difference in Wi-Fi signal level, magnetic field sensor distortion, step length determination. There are no single solution for any of this problem.

3. METHODOLOGY

In the previous section potentially usable technologies were described and available indoor navigation techniques were introduced. Not all the techniques can be used on smartphones since such methods as UWB positioning requires the usage of additional hardware. Since one of the goals of the thesis was to implement the cheapest and easiest solution, no additional hardware (except the smartphone) were used. The current device choice of this thesis is a smartphone Google Nexus 5 working under Android 4.4.4 (KitKat); thus the methods described in this chapter can be applied for this device and for the devices with similar hardware and software characteristics.

According to the discussion shown in Chapter 3.1.2 the novelty of Nexus 5 is a hardware step detector and step counter. In this chapter the usage of step detector in different navigation methods is described, the main benefits and issues are also shown. Moreover, the details of the implementation of the “step counter – based” tracker are also discussed.

3.1 Materials and Preparation

For software development author used an open-sourced platform called Eclipse IDE, running under ArchLinux operating system which is described more circumstantially in the Chapter 3.1.3. Moreover, the smartphone Google Nexus 5 under Android KitKat 4.4.4 was used to test software made by author. Furthermore, Navizon Inc. provided a set of indoor navigation software that was also tested and used for comparison of two different step detection methods. The main results and conclusions can be found in chapter 4.

3.1.1 Smartphone Review

The main purpose of using an ordinary smartphone in this project was to decrease the expenses related to the developing of a new hardware. Another goal was to test the simplicity of open-sourced libraries and tools provided by Google and to create a simple software solution that could be used for testing hardware and algorithms.

Several different candidates were chosen: LG Google Nexus 4, LG Google Nexus 5 and HTC One. All these phones are working under Android OS. Since the most significant characteristic is navigation features (i.e. the amount of different sensors), the description below involves only a short hardware and sensors details.

Summing up the advantages and disadvantages of the smartphones in the Appendix C, such as standby time, price, amount of sensors, the choice in favor of using Google Nexus 5 as the base device was made [8].

3.2 LG Google Nexus 5

In this thesis LG Google Nexus 5 was taken as a test model since this device has 2 additional navigation sensors on board and costs less than other comparable models. The main goal of using this particular device is to compare hardware implemented step detector and software implemented step detector to estimate the benefits and limitations of both.

LG Google Nexus 5 (Figure 3.1) was announced and released on 31 Oct 2013. It has 2048 MB RAM and quad core processor that makes it one of the most powerful pocket mobile devices. Nexus 5 is the first phone where 2 new types of navigation sensors were used: step detector and step counter. Both sensors are implemented in hardware for low power consumption [6], [7].

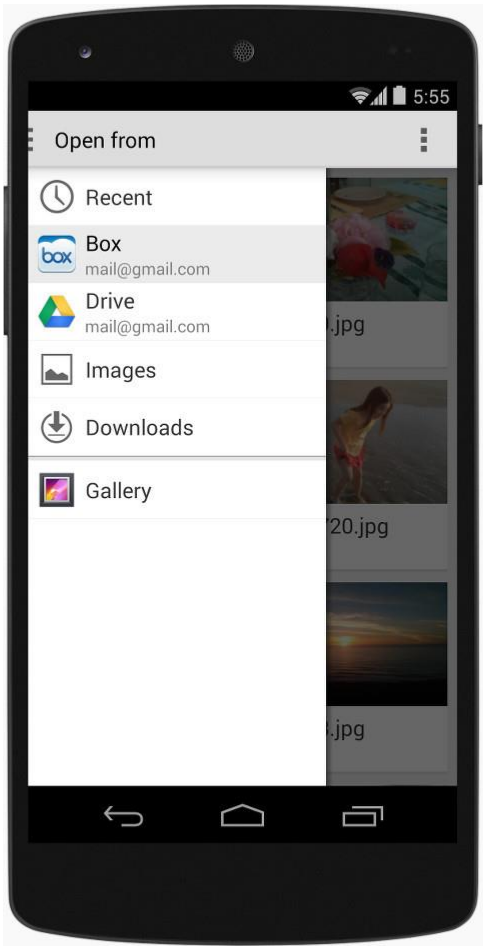


Figure 3.1. LG Google Nexus 5

3.2.1 Magnetic Field Sensor

The current device uses the magnetic field sensor based on Hall Effect sensing. The main advantages of using this method and theoretical circumstances were described in chapter 2.1.1.5. In this thesis magnetic field sensor was used as a compass to obtain the current heading but there is a set of specific features that should be taken into account.

First of all, there is *magnetic variation* (declination) effect which is the difference between magnetic North and true North. In fact, the current distance between true and magnetic North Pole is about 810 kilometres and it is currently increasing by 65 kilometres per year. So far is Earth's magnetic field is moving not in a straight line, the difference between the poles can be different in different locations. According to National Geophysical Data Center, the declination in Tampere area is 8° 8' 44" to the East and changing by 8.0' to the East per a year. This difference declination was considered in this thesis on the stage of heading calculation.

Secondly, there is a difference between the magnetic North and the direction in which the compass is pointing, called *compass deviation*. As there a lot of magnetic field sources. Some of them are permanently build in the walls of the building, some are caused by an electronic instruments and equipment. Compass deviation cannot be totally compensated without getting a prior knowledge about location and the magnetic field levels. In the thesis compass deviation was partially compensated by low-pass filter with the following algorithm:

```
public class AngleLowpassFilter {
 //Deque size
 private final int LENGTH = 10;
 private double sumSin, sumCos;
 private ArrayDeque<Double> queue = new ArrayDeque<Double>();
 //adding angle to the deque
 public void add(double radians){
  sumSin += Math.sin(radians);
  sumCos += Math.cos(radians);
  queue.add(radians);
  if(queue.size() > LENGTH){
   double old = queue.poll();
   sumSin -= Math.sin(old);
   sumCos -= Math.cos(old);
  }
 }
 //Compute average sine and cosine
 public double average(){
  int size = queue.size();
  return (double) Math.atan2(sumSin / size, sumCos / size);
 }
}
```

Program 1. *Lowpass filter class*

Magnetic compass should be also calibrated from time to time since the compass headings can be affected by environmental interference. Calibration can be easily done by waving the smartphone in a figure “8”, during the movement the forward axis is tilled about 45 degrees in each direction and sideway axis inverted there and back. In the thesis calibration was also done by rotating the device along three axes: full rotation with the screen facing up, full rotation rolling sideways and one full rotation pitching forward.

3.2.2 Step Counter and Step Detector

In the section 2.1.2.2 the basics of PDR with accelerometers were presented and step detection technique was shown. In Google Nexus 5 step detector is built in a hardware that makes PDR much easier. Step detector runs on one of the low-power processor’s cores and analyses the output of accelerometers. If the step was detected, it generates an event that can be easily handled with API instruments (Program 1). It also wakes step counter to initiate counting.

```
//Sensor event listener
private final SensorEventListener mListener = new SensorEventListen-
er() {
  @Override
  public void onSensorChanged(SensorEvent event){
   if(event.sensor.getType() == Sensor.TYPE_STEP_DETECTOR){
    Step st = new Step(mStamp, mSensorX, mSensorY, mSensorZ, mHead-
ing);
    mRunManager.insertLocation(st);

    //Count the amount of steps from application launch
    mStepCounter++;
   }
  }
}
```

Program 2. *Example of using step counter sensor on Android*

In chapter 4 the comparison between software and hardware implemented step detectors is shown. Currently, step counter and step detectors can be found in Google Nexus 5 only, but, according to the information from Google Android official web page, they are working with their chipset partners to bring them to all the new devices.

3.3 Software Description

In this section the software used for application development is presented. Section starts from the operation system overview then the set of IDE, its configuration and settings are shown.

3.3.1 ArchLinux

ArchLinux is one of the most fast-growing distributions. It is a binary distribution and exists in two different implementations: for i686 and x64 architecture. In the thesis x64 version was used since it allows using more than 4GB of RAM. As a Gentoo, ArchLinux is called “metadistribution” since the most part of users have unique set of programs and OS configuration. Moreover, due to the unique packet format and flexible packet manager, ArchLinux can be configured for almost every task. This is also a rolling release distribution, which means that the user gets new versions of software right after the release date.

3.3.2 Eclipse IDE

Eclipse is an open-source integrated environment for developing and testing cross-platform applications. It can be used to develop applications in almost every language using the flexible extension system. In this thesis work Eclipse of version 4.3 “Kepler” was used.

Eclipse gain popularity mostly as one of the best extension development platform: any developer can extend Eclipse with self-written modules like ADT, CDT, JDT. Currently a huge amount of extensions allows user to work only with typical programming languages but also with typesetting languages like LaTeX, networking application such as telnet and database management systems. Eclipse also supports configuration management and version control systems.

Eclipse and Sun Java Developer Kit (JDK) were installed using “Pacman” packet manager with the following commands:

```
# pacman -S eclipse
# pacman -S jdk
```

Program 3. *Eclipse and Sun JDK installation*

By default Eclipse allows to develop in Java only, so Android Developer Tools (ADT) plugin was also installed.

To add the ADT plugin to Eclipse the following instruction were used:

1. Start Eclipse, then select Help > Install New Software.
2. Click Add, in the top-right corner.
3. In the Add Repository dialog that appears, enter "ADT Plugin" for the *Name* and the following URL for the *Location*:

https://dl-ssl.google.com/android/eclipse/

4. Click OK.
5. In the Available Software dialog, select the checkbox next to Developer Tools and clickNext.
6. In the next window, you'll see a list of the tools to be downloaded. ClickNext.
7. Read and accept the license agreements, then click Finish.
8. When the installation completes, restart Eclipse.

After creating the Android project, Google Play services were installed and configured to provide the access to Google Maps API. The library project at from “<android-sdk>/extras/google/google_play_services/libproject/google-play-services_lib/” was copied to the folder with Android project. Then the library project was copied into Eclipse workspace and the reference to Google Play services was created. After that the following tag was added to the manifest file of the project as a child of <application> component:

```
<meta-data android:name="com.google.android.gms.version"
   android:value="@integer/google_play_services_version" />
```

3.3.3 Google Android SDK

Google Android OS is now the most popular mobile device platform – it takes about 80% of total volume on mobile OS market. Android SDK provides all the tools and libraries that are necessary to build, debug and test an android application. The most popular way to develop is to use it in pair with Eclipse IDE: both of it can be downloaded for free from the official web-sites. Android Eclipse plug-in is called ADT (Android developer tools) also provides an emulator that can be adjusted to emulate some specific kind of hardware. In the thesis Google ADT of version 4.4 (KitKat) were used since this version provides interfaces for managing step counter and step detector.

The application, created during this thesis, is based on the class called “fragment”. Started from Android 3.0 fragments allow to create a universal code for all the Android devices and display types. Fragment is an independent component with a separate interface and life cycle. It can be reused in several different parts of user interface depending on the particular UI thread. Class diagram is represented in appendix A and appendix B.

3.3.4 Google Maps API

Google Maps was released as beta in 2005 and in the same year the first API was provided. Google provides the Google Maps API for free, and in return they require the resulting application being free as well. The largest benefit of using Google Maps API is it’s flexibility and multiple platform support. Any application based on Google Maps can be adapted to be used on another software platform with minimum changes in the program logic.

After getting a free Google Maps key the map was integrated to the android application with the code shown in Program 4. The reference to Google Maps was stashed and the coordinates of Tampere University of Technology were set as an initial point where the camera is moving by default. Map type was set as “satellite” by default but the view can be changed in a runtime too. Next the handler was added to manage the map clicks and show the route on the map by click.

```
@Override
public View onCreateView(LayoutInflater inflater, ViewGroup par-
ent,Bundle savedInstanceState) {
 v = super.onCreateView(inflater, parent, savedInstanceState);
 mGoogleMap = getMap();
 //TUT coordinates
 LatLng TUT = new LatLng(61.449776, 23.854630);
 //move camera to TUT
 mGoogleMap.moveCamera(CameraUpdateFactory.newLatLngZoom(TUT,
19));
 mGoogleMap.setMapType(GoogleMap.MAP_TYPE_SATELLITE);
 //draw the route by click
 mGoogleMap.setOnMapClickListener(new Google
Map.OnMapClickListener() {
  @Override
  public void onMapClick(LatLng point) {
  if(startMarkerOptions == null){
   startMarkerOptions = new MarkerOptions()
    .position(point)
    .title(getString(R.string.run_start));
   mGoogleMap.addMarker(startMarkerOptions);
   updateUI(point);
  }else{
   startMarkerOptions.position(point);
   mGoogleMap.clear();
   mGoogleMap.addMarker(startMarkerOptions);
   updateUI(point);
  }
 }
});
```

Program 4. *Example of using Google Maps API in the Android application*

4. IMPLEMENTATION AND TESTING

In the first part of the chapter, the details of practical implementation will be described: the structure of application will be given, and user interface will also be discussed. Next, database structure will be shown and the results of testing the Android application will be also represented. Finally the comparison of two step detection methods will be given and corresponding conclusions will be presented.

4.1 Indoor Tracker Application Structure

RunTracker is an Android application based on ADT which main goal is to estimate efficiency of build-in step detector and measure the total positioning error while using step detector and magnetic compass. It can also be utilised as a simple indoor tracker. The application is supposed to track the user's movement in the indoor areas without using any external absolute positioning system by computing the position using self-contained sensors only.

The application contains of 3 main screens: "RunList" (initial screen), "RunFragment" and "MapFragment". Every screen consists of separate class with individual functionality. Class diagram can be found in Appendix 1 and Appendix 2, respectively (the basic and the most important classed are included in this diagram since the total amount of classes is too large). During the first start user is able to see the blank screen with the button "Add" in the top right corner. In this screen user is also allowed to remove available runs (if they exist). After adding a new run user can start and stop tracking on the "RunFragment" screen and draw the track on the map using GPS data as an initial position or input the initial position manually. "RunFragment" screen also shows the data from all the following sensors: gyroscope, accelerometers, GPS, elapsed time from satellites, step counter, step detector, current data, time interval between the steps. Not all the information listed here is used in this thesis but it can be used later for a future research.

User is able to draw the route on the Google map. It can be done by clicking on the "Map" button on the "RunFragment" screen. Before the route will be drawn, user must input the step length manually and choose the initial point (either using GPS or manually by clicking on the map). User interaction diagram can be found in the Figure 4.1.

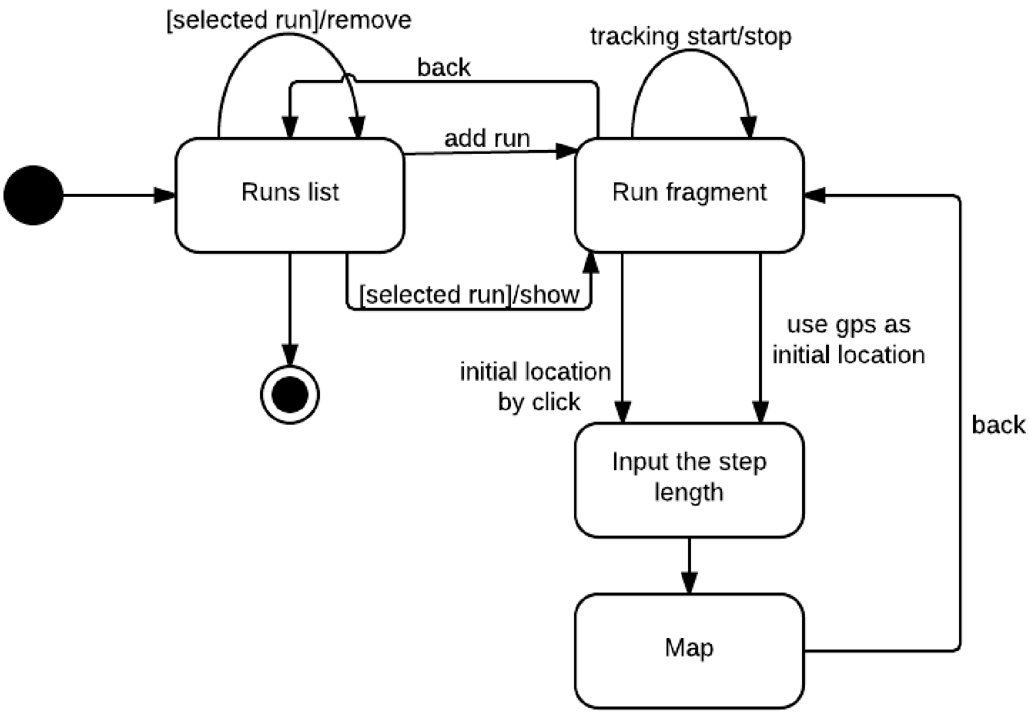


Figure 4.1. RunTracker user interaction diagram

All the tracks done by user are kept in the SQLite database; tracks can be added or removed during the runtime by the long tap on the corresponding track.

The application is processing the data from magnetometer, step detector, and then combine it with information about the step length. After that the information is added to a database shown in the Figure 4.2. It consists of two tables: "run" table (for keeping the run series) and "location" table (for keeping the information about every step done).

"run" table

_id	start_date
1	14105297134556
2	14105294356754

"location" table

run_id	timestamp	xaxis	yaxis	zaxis	heading
1	14105297134556	-1.7843647	5.435435	8.458564	239.1247
1	14105297195642	-1.7842546	4.235687	8.899654	240.6587
2	14105294356754	5.689741	9.365241	1.256234	12.6985
2	14105294356876	5.675125	8.568941	5.235687	16.1245

Figure 4.2. RunTracker database structure

4.2 Application Testing

One of the goals of this thesis work was to create a simple application showing the aspects of using build-in step detectors in smartphones. After building the interface and implementing the main features the set of tests were done. Moreover, the application called Navizon Indoors 2.0 Demo was also tested. This application was provided by Navizon Co. specially for testing purposes and the full feedback was sent to a company after the results of tests were processed. Testing objectives:

- compare step detectors and make a decision about the expediency of using hardware implemented step detectors in a real software;
- test the real software provided by indoor navigation company, get the main advantages and weaknesses of the methods, used in this application;
- test the software created by author;
- compare the testing results and get the strong and weak sides of methods used in this thesis.
- suggest the way of improving accuracy in both applications

4.2.1 Testing of Step Detectors

The main idea of this experiment is to estimate the error in step recognition algorithms implemented in two different ways. For this purpose 5 sets of test were done: with 100, 200, 300, 400 and 500 steps, respectively. Two applications were started simultaneously, both were using the same set of accelerometers. During the tests smartphone was hold in front of the user, stair were avoided by the slight changes in the floor levels took place.

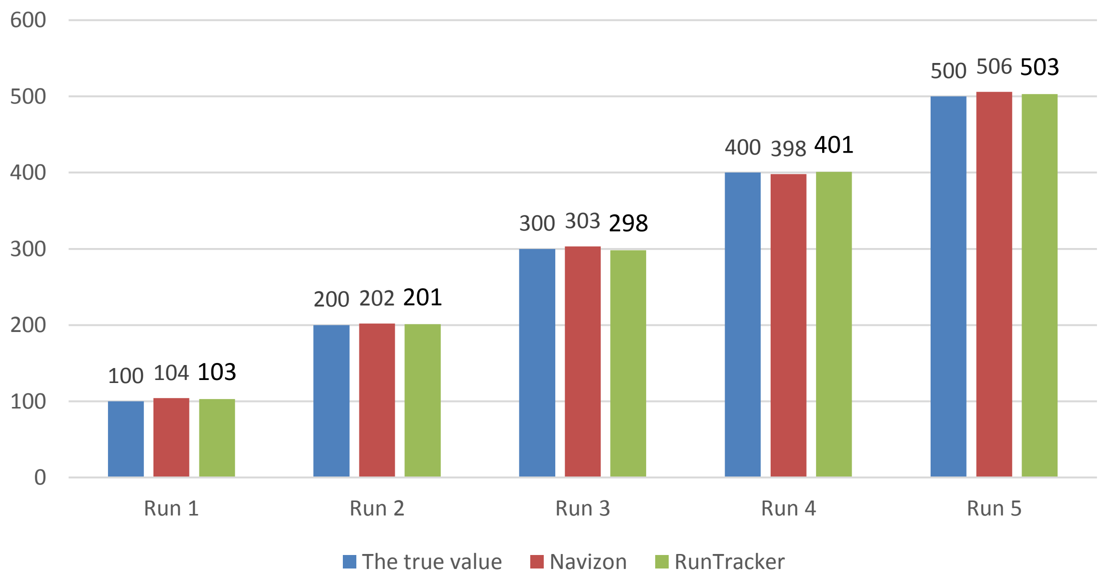


Figure 4.3. Comparative charts of step detectors

Figure 4.3 illustrates the results of the test. The error of Navizon (red bar) step detector is a bit higher by it can be clearly seen that both step detectors shown almost absolute accuracy. Since both of the step detectors are proprietary i.e. it is restricted to get an access to the source code and hardware part, only the assumptions can be made.

Table 4.1 shows the absolute and percentage error of step detectors. The very exceptional thing is that the absolute error is almost the same and does not related to the amount of steps done. One of the reasons is that step detectors fail on the stage of initial step since the acceleration of the first step is usually too low. As it shown in the table below, default step detector implemented in smartphone is more accurate than the one implemented in software. In general both of the methods a reliable enough to be used in a real software but Google step detector has a good advantage of power consumption.

Table 4.1 Step detection error

Number of steps	Navizon step detector error		Nexus 5 step detector error	
	Absolute error (in steps)	Percentage error	Absolute error (in steps)	Percentage error
100	4	4%	3	3%
200	2	1%	1	0.5%
300	3	1%	2	0.66%
400	2	0.5%	1	0.25%
500	6	1.2%	3	0.6%

4.2.2 RunTracker

The application was tested in 3 different areas: city mall, outdoor area, university campus. Calibration was done before every test.

Experiment 1:
Location: Outdoor area
Coordinates of start: 61.446693, 23.853542
Area properties: The application was tested on the straight pedestrian path between student’s dormitory and city mall. The total distance is about 550 meters (723 steps), several crossroads were passed by and quite high magnetic field fluctuations were notices during the test.
Results: The application showed good results of path tracking during almost the whole way as it presented in the Figure 4.4. In the end of the path, on the crossroad, the magnetic compass started to show the wrong heading with the error about 30˚. This fact allows to make and assumption that in this particular place there is a huge magnetic field distortion cased, probably, by some source located in city mall or nearby. The total amount of steps counted was 718, which is 5 steps smaller than a real amount of steps.

Figure 4.4. Testing of RunTracker in the outdoor area

Total distance error is about 35 meters that can be considered as satisfactory. The percentage error is shown in the Figure 4.5.

Experiment 2:

Location: City mall

Coordinates of start: 61.450459, 23.851056

Area properties: The city mall is located in the center of local district. The total area of the building is about 15000 square meters, several supermarkets and boutiques are located there. City mall consists of several wide, square market areas connected with narrow corridors. Full Wi-Fi coverage is provided. The magnetic field is quite stable but the compass was suffering from compass deviation and the heading was different from the true value according to visual estimation.

Results: The total amount of steps done was 519 step: the amount of step to cross the city mall from 2 side and come back to the initial point. The amount of steps counted was a bit larger – 521 step. The error could be caused by the large amount of people in supermarkets and atypical movement of user due to the human's traffic. Moreover, during the experiment the direction of movement were changed quite frequently and sideways movement took place as well. The final positioning error reached 27 meters or about 6.92%, which is the best result between the three tests. The comparison charts are shown on the figure 4.5.

Experiment 3:

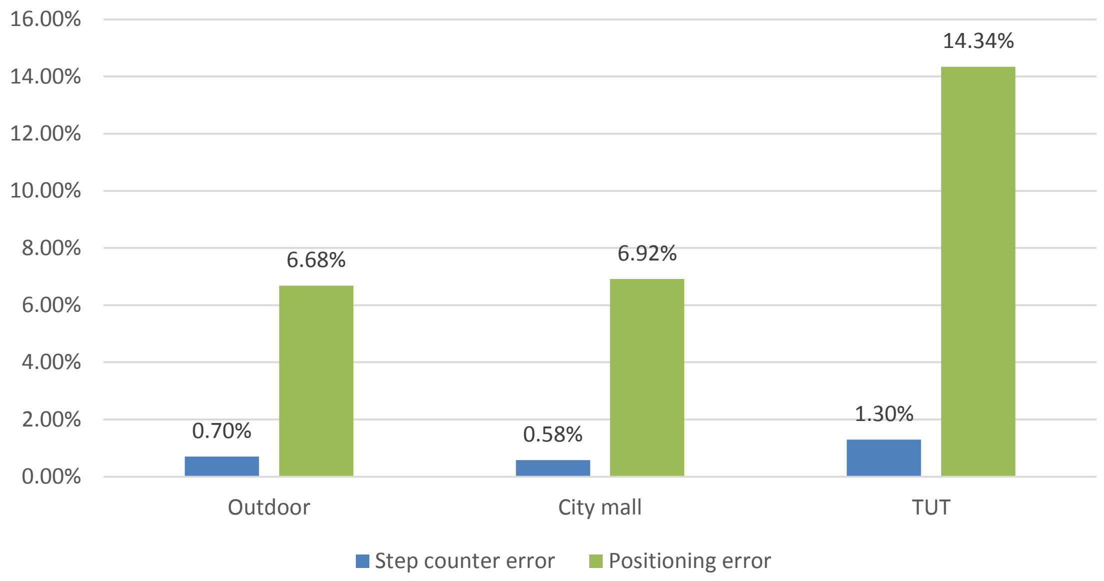


Figure 4.5. RunTracker positioning and step counter errors

Location: Tampere University of Technology
Coordinates of start: 61.448917, 23.859137
Area properties: The area of university is very noisy in terms of existence of different signal sources including the sources of magnetic field. The area consists of several narrow corridors and halls. The total distance covered is about 230 meters.
Results: Due to the strong magnetic field interference, magnetic compass was suffered from sharp fluctuations that caused the final error of 33meters. The error in step detection reached 4 steps which is a bit more than average results.
Figure 4.5 shows the error in position determination of all the three tests. As it can be seen from the corresponding bars, the largest error took place in the Tampere University of Technology campus. Due to a high amount of magnetic field sources and high magnetic distortion, the total error reached more than 14%, which can be considered as very imprecise. Results obtained from the outdoor area and city mall can be considered as satisfactory and equal since the difference in position determination is almost the same in both cases.

4.2.3 Navizon

Navizon Indoors Demo 2.0 was provided by Navizon Co., the company was founded in 2005 as pioneer of indoor navigation services. The application is based on trilateration method that allows to compute mobile device's current longitude, latitude by using Wi-Fi and mobile broadband signals in addition to GPS. Application may run on smartphones, tablets or custom devices both in Android and iOS. Fingerprinting is the main method used to determine user's position, company provides the common database of indoor location which provide a good coverage in the Unites States.

Before testing was done, a set of preparations were made: the maps of indoor locations were imported to a cloud server, the fingerprinting of every indoor location was done as well.

Totally 3 sets of tests were done in different indoor location: student's dormitory with a huge Wi-Fi access points density, city mall with big areas without corridors, university campus with a lot of narrow corridors.

Experiment 1:

Location: Students dormitory

Coordinates: 61.446461, 23.852831

Area properties: Small area with a lot of tiny rooms and several corridors. There were about 20 Wi-Fi routers available in every point but the signal is very weak due to the thick walls. All the area was totally covered with Wi-Fi.

Results: The first test was done using magnetometer as a primary heading source. The result was unsatisfactory since the magnetic distortion was too high and the application started to determine the position in a wrong way (Figure 4.6, the green line is a real track).

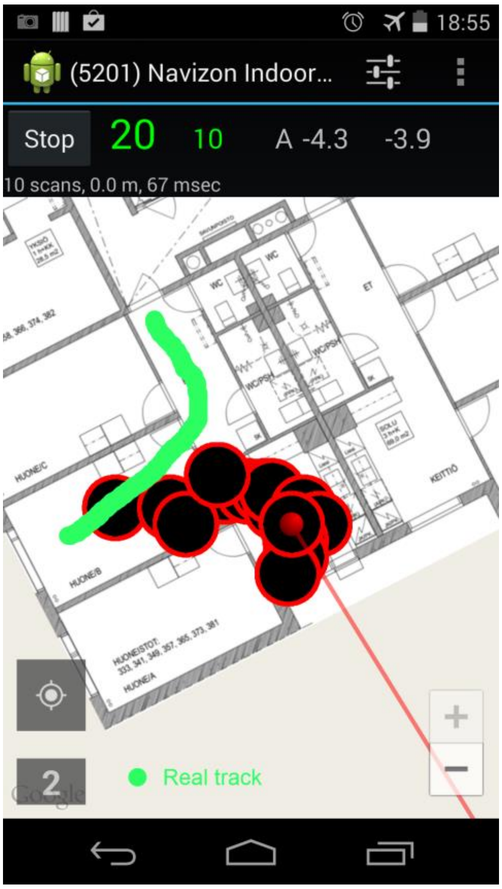


Figure 4.6 Testing of Navizon application in the dormitory

Next, the gyroscope was selected as primary heading source and the initial position was determined quite precisely with the error about 3 meters. After the movement was started, the application started to use inertial sensors in order to improve the position estimation done with Wi-Fi and the positioning error was lying between 2-3 meters, respectively.

Experiment 2:
Location: City mall
Coordinates: 61.450701, 23.849897
Area properties: Long and wide halls with two narrow, crossed corridors. The area is totally covered with Wi-Fi access points. The area properties are the same as were described in *experiment 2* of section 4.2.2.
Results: The application showed a very good result both with compass and gyroscope orientation. The average positioning error was between 2-3 meters. Some inaccuracy took place in the spots of low fingerprinting coverage. Sometimes step detector worked not enough fast due to unknown reasons and stuck in the moments when the user turned back. The Figure 4.7 shows the real route (green line) and computed route determined by an application (red line). It can be noticed that computed route differs from real route. It can be caused by Wi-Fi distortion since the amount of Wi-Fi access points is not very high and the signal could be attenuated by people, walls and other obstacles.

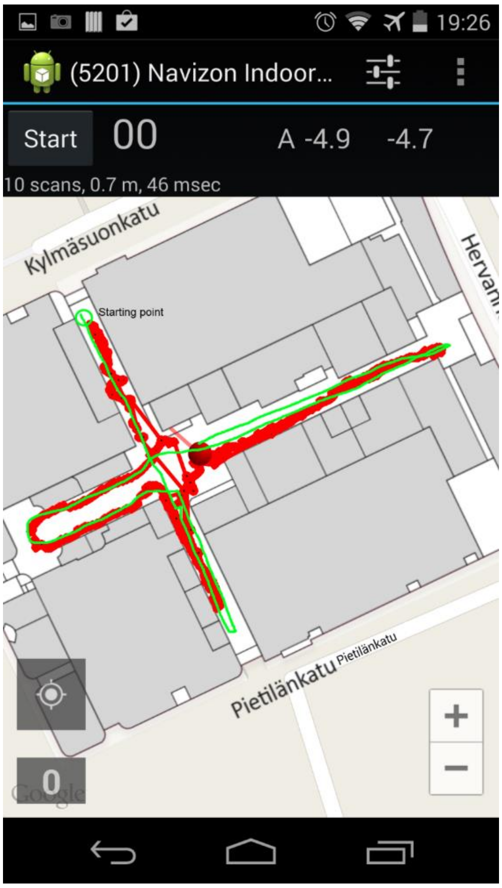


Figure 4.7. Testing of Navizon application in the city mall

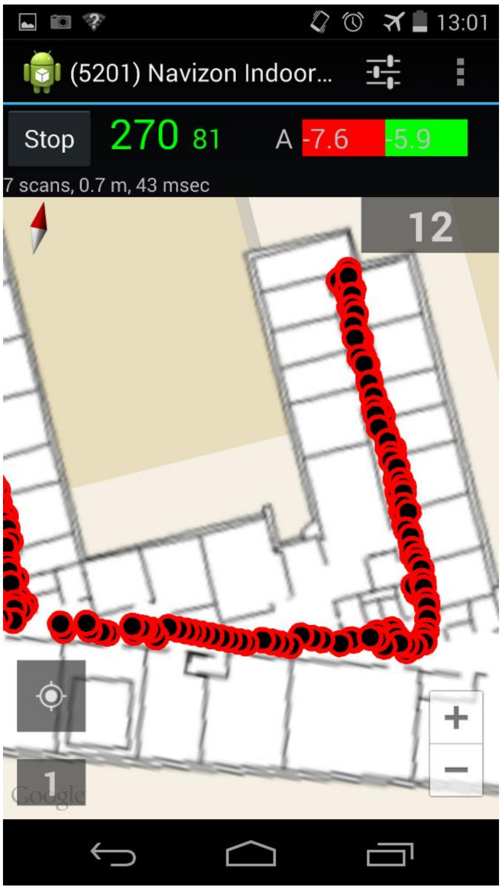


Figure 4.8 Testing of Navizon application in Tampere University of Technology

Experiment 3:
Location: Tampere University of Technology
Coordinates: 61.449819, 23.854784
Area properties: Area consists of long and narrow corridors with several rooms. It has a fairly good Wi-Fi coverage and the map is very precise, so the error should be quite low. The corridors are overloaded with different types of magnetic field sources and digital compass should be disabled here.
Results: The initial position was defined with an error of 10 meters but after several steps the correction with inertial sensors have been done. Gyroscope was set as a primary source and showed precise movement direction. Changing with magnetometer didn't increase the positioning error despite on a high density of electronic devices. The tracking have been done very precisely the average error during the experiment obtained less than 2 meters.

4.3 Baseline Results

RunTracker application showed good results in open areas and in the areas with wide halls. It works rather well in case of low magnetic field distortion. This application was mainly created in studying and testing purposes thus comparison of corresponding total positioning error with the position estimation provided by Navizon Co. cannot be objective. According to the fact that tracking was done without using external signal sources, the result of tracking can be considered as good. The results of testing built-in step detector showed robustness and high accuracy of the sensor.

In general, the application suffers from magnetic interference and even small magnetic field fluctuations can sharply increase positioning error. The final positioning error and step detection error can be found in Figure 4.5.

Navizon is very precise and flexible application, uses a mixture of techniques to estimate the position. But the application provides precise positioning only in case when all the conditions were compiled: accurate fingerprinting, precise mapping and good Wi-Fi/Bluetooth coverage. It does not work autonomously without utilizing Wi-Fi access points. The company declared position error in the range between 3-5 meters and this accuracy was proved during the experiments.

Moreover, in case of distorted compass readings (that usually happens if calibration have not been done beforehand) the application can show the wrong position. Also the application works incorrectly when user just shakes the phone and does not move himself or the phone is not in the front of the user while moving.

In general, the application has a user-friendly interface, flexible settings and utilizes all the latest indoor navigation techniques that can be implemented in smartphone. Reliability of application was approved during several experiments.

5. CONCLUSIONS

The thesis discusses the latest indoor navigation methods, describes the main implementation points of indoor navigation application called RunTracker, shows the results of the built-in inertial sensors testing. According to the tests done in student's dormitory, university campus and city mall, tracker based on compass and step detector is quite ineffective since some areas have got a very strong magnetic field level that can rapidly increase the error in magnetometer outputs. Furthermore, magnetic field sensor should also be calibrated before usage, the process takes about 2 minutes and comprises of turning around the smartphone (the technique is described in section 3.2.1). The final error after several tests reached about 15-20 meter and strongly depends on the area of tests. The accuracy is quite low since the most of commercial indoor navigation solutions (e.g. "Navizon", "IndooRS") guarantee accuracy between 2-5 meters. The performance of tracker can be improved in several ways:

Compass correction should be done using accelerometers as a secondary heading source. Due to the high accelerometer drift it should not be used as a primary heading source, but in a pair with magnetic compass the results should be much better. In this case, Kalman filter should be used to get better results.

Use a compass/step detector in a complement with other navigation techniques. Better results can be achieved by using the methods described in this thesis in section 2.1.2.1 in a complement with Bluetooth/Wi-Fi navigation methods.

During the testing of Navizon Indoor Demo 2.0 several possible improvements were found: using of fingerprinting instead of SLAM can improve the performance and make the preparation process less complicated, automatic switching between gyroscope and magnetic compass could provide more robustness in heading determination. Moreover, combining current methods with magnetic field map-matching could improve positioning accuracy.

Finally, the built-in step detector is approved as a reliable, robust and low power-consumptive sensor that can be used in navigation purposes.

The most important issue of the navigation method used in this thesis is a large positioning error. This issue could be totally avoided if the application could use accelerometers instead of magnetometer (or use magnetometer as an additional heading source) to estimate the movement direction. Moreover, the length of steps was determined in quite inefficient way described in [39]. Accelerometers could be used to determine the step length dynamically as in [30].

In general, the application cannot be considered as a ready-to-use product. It suffers from unfriendly user interface and lack of functionality which is a result of single person development. The best way to improve would be to cooperate with some indoor navigation company and use the application as a module for a ready solution.

During this thesis work the area of indoor navigation was deeply explored. The main perspectives of this field are related to civilian and emergency usage. Despite the apparent similarity, these areas are quite differ from each other. Thus, civilian indoor application pretended be more multipurpose i.e. providing not only navigation service inside the building but also additional services like weather forecast, bus schedule, shopping discounts and sales. Civilian indoor applications are mainly based on getting the information from different source and combining several methods. The results reached during this thesis work can be considered as a good platform of using different combinations of sensors in a civilian application. One of the future research directions is using of step detector in map-matching algorithms.

On the other hand, emergency usage of smartphones is always based on the fact that there is no additional signal sources and the device determines it's position based on built-in sensors only. Emergency usage is not only the using of smartphones by fire brigades and ambulance but also by people who got into emergency situation. Earthquakes and avalanches are always the most difficult situation where knowing of exact people's location is needed. In this case UWB positioning tends to be one of the most promising technology that were not yet implemented in smartphones.

REFERENCES

[1] J. Bancroft, “Multiple inertial measurement unit fusion for pedestrian navigation,” Ph.D. dissertation, the University of Calgary, Canada, 2010.

[2] D. Han, M. Lee, L. Chang, H. Yang,” Open Radio Map Based Indoor Navigation System,” Department of Computer Science, Korea Advanced Institute of Science and Technology.

[3] A. R. Golding, N. Lesh, ”Indoor navigation using a diverse set of cheap, wearable sensors,” *Proceedings of the third International Symposium on Wearable Computers*, San Francisco, California, pp. 29-36, October, 1999.

[4] K. Abdulrahim. Integrating Low Cost IMU with Building Heading in Indoor Pedestrian Navigation. In *Journal of Global Positioning Systems* 10.1, pp. 30–38, 2011.

[5] H. Leppäkoski, J. Collin, and J. Takala, “Pedestrian navigation based on inertial sensors, indoor map and WLAN signals”, in *Proc. ICASSP*, 2012.

[6] Nexus 5 round-up: 5 awesome new features, release date, price, specs and all we know so far. [WWW]. [Accessed on 27.3.2014]. Available at: http://www.phonearena.com/news/Nexus-5-round-up-5-awesome-new-features-release-date-price-specs-and-all-we-know-so-far_id47236

[7] Google Nexus 5 [WWW]. [Accessed on 27.3.2014]. Available at: http://www.phonearena.com/phones/Google-Nexus-5_id8148

[8] New HTC One (M8) release date, specs and features: What you need to know about the new HTC One for 2014 [WWW]. [Accessed on 27.3.2014]. Available at: http://www.pcadvisor.co.uk/buying-advice/mobile-phone/3502531/htc-one-m8-release-date-specs-features-uk/

[9] Pedestrian Navigation [WWW] [Accessed on 27.4.2014]. Available at: http://www.navipedia.net/index.php/Pedestrian_Navigation

[10] A. Küpper, “Location-Based Services: Fundamentals and Operation,” Wiley,2005.

[11] RFID [WWW] [Accessed on 30.4.2014] Available at: http://www.packagingdigest.com/rfid

[12] G. Welch, G. Bishop (2001). *An Introduction to the Kalman Filter*.[WWW] [Accessed on 27.4.2014] Available at: http://www.cs.unc.edu/~tracker/media/pdf/SIGGRAPH2001_CoursePack_08.pdf

[13] D. Titterton, J. Weston, “Strapdown Inertial Navigation Technology (IEE Radar, Sonar, Navigation and Avionics Series),” 2004.

[14] B. Graf, J. M. H. Wandosell, C. Schaeffer, “Flexible path planning for nonholonomic mobile robots,” in *Proc. of EUROBOT'OI*, pages 199-206, 2001.

[15] A. L. Kornhauser, C. E. White, D. Bernstein, “Some map matching algorithms for personal navigation assistants,” Transportation Research, Part C 8: pages 91 - 108, 2000.

[16] K. Chon, J. Yang, S. Kang (2005). The map matching algorithm of GPS data with relatively long polling time intervals. *Journal of the Eastern Asia Society for Transportation Studies*, Vol. 6, pages: 2561 - 2573.

[17] Widyawan, M. Klepal, S. Beauregard, “A backtracking particle filter for fusing building plans with PDR displacement estimates,” in *Proc. of the 5th Workshop on Positioning, Navigation and Communication 2008* (WPNC'08), 2008.

[18] B. Krach, P. Roberston, “Cascaded Estimation Architecture for Integration of Foot-Mounted Inertial Sensors,” in *Proc. of IEEEIION PLANS 2008*, Monterey, CA, May 2008, pp. 112-119.5.

[19] M Youssef, A. Agrawala and A. Shankar, “WLAN location determination via clustering and probability distributions,” in *Proc. 1st IEEE Int. Conf. on Pervasive Computing and Communication*, Dallas Fort-Worth, TX, USA, Mar.23-26, 2003.

[20] Google Gets in Your Face [WWW] [Accessed on 27.6.2014]. Available at: http://spectrum.ieee.org/consumer-electronics/gadgets/google-gets-in-your-face

[21] How New Indoor Navigation Systems Will Protect Emergency Responders By Mark Harris. [WWW]. [Accessed on 12.1.2014]. Available at: http://spectrum.ieee.org/static/how-new-indoor-navigation-systems-will-protect-emergency-responders.

[22] R. Henniges, “Current approaches of Wi-Fi positioning”, Germany,TU-Berlin, 2012.

[23] O. J. Woodman (2007, August), “An introduction to inertial navigation”, University of Cambridge [WWW]. Available at: http://www.cl.cam.ac.uk/techreports/UCAM-CL-TR-696.pdf

[24] Region monitoring and iBeacon [WWW] [Accessed on 01.08.2014] Available at: https://developer.apple.com/library/ios/documentation/userexperience/Conceptual/LocationAwarenessPG/RegionMonitoring/RegionMonitoring.html

[25] Beacon for developers [WWW] [Accessed on 01.08.2014] Available at: https://developer.apple.com/ibeacon/

[26] Indoor navigation in malls [WWW] [Accessed on 01.08.2014] Available at: https://www.navigine.com/blog/view?id=59&title=Indoor%20navigation%20in%20malls

[27] A. Bensky, “Wireless Positioning: Technologies and Applications,” Northwood: Artech House Inc., 2008

[28] T. K. K Tsang, M. N El-Gamal, “Ultra-wideband (UWB) communications systems: an overview,” in *the 3rd Int. IEEE-NEWCAS Conf.*, 2005, pp. 381 – 386.

[29] A. F. Molish, P. Orlik, Z. Sahinoglu, and J. Zhang, “UWB-based sensor networks and the IEEE 802.15.4a standart – a tutorial,” in *Proc. Chinacom*, 2006.

[30] N. Zhao, “Full-featured Pedometer Design Realized with 3-Axis Digital Accelerometer,” *Analog Dialogue* 44-06, June 2010.

[31] J. A. Castellanos, J. M. Martnez, J. Neira, and J. D. Tardos, “Experiments in multisensor mobile robot localization and map building,” in *3rd IFAC Symp. on Intelligent Autonomous Vehicles*, pages 173–178, 1998.

[32] R. M. Faragher, R. K. Harle, “SmartSLAM - an Efficient Smartphone Indoor Positioning System Exploiting Machine Learning and Opportunistic Sensing,” in *Proc. of the 26th Int. Tech. Meeting of the Satellite Division of the Inst. of Navigation*, ION GNSS+ 2013, September 16-20, Nashville, TN, 2013.

[33] M. S. Grewal, A. P. Andrews, “Kalman Filtering — Theory and Practice Using MATLAB”, Wiley, 2001.

[34] F. Porikli, O. Tuzel (2006, June), “Covariance Tracking Using Model Update Based on Lie Algebra,” in *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR).*

[35] McKinsey, “Executive summary” [WWW] [Accessed on 05.07.14] Available at: http://www.nyc.gov/html/fdny/pdf/mck_report/executive_summary.pdf

[36] W .Madden, M. Milford, G. Wyeth, “Continuous Appearance Trajectory SLAM,” in *Robotics and Automation (ICRA),* 2011 IEEE Int. Conf.

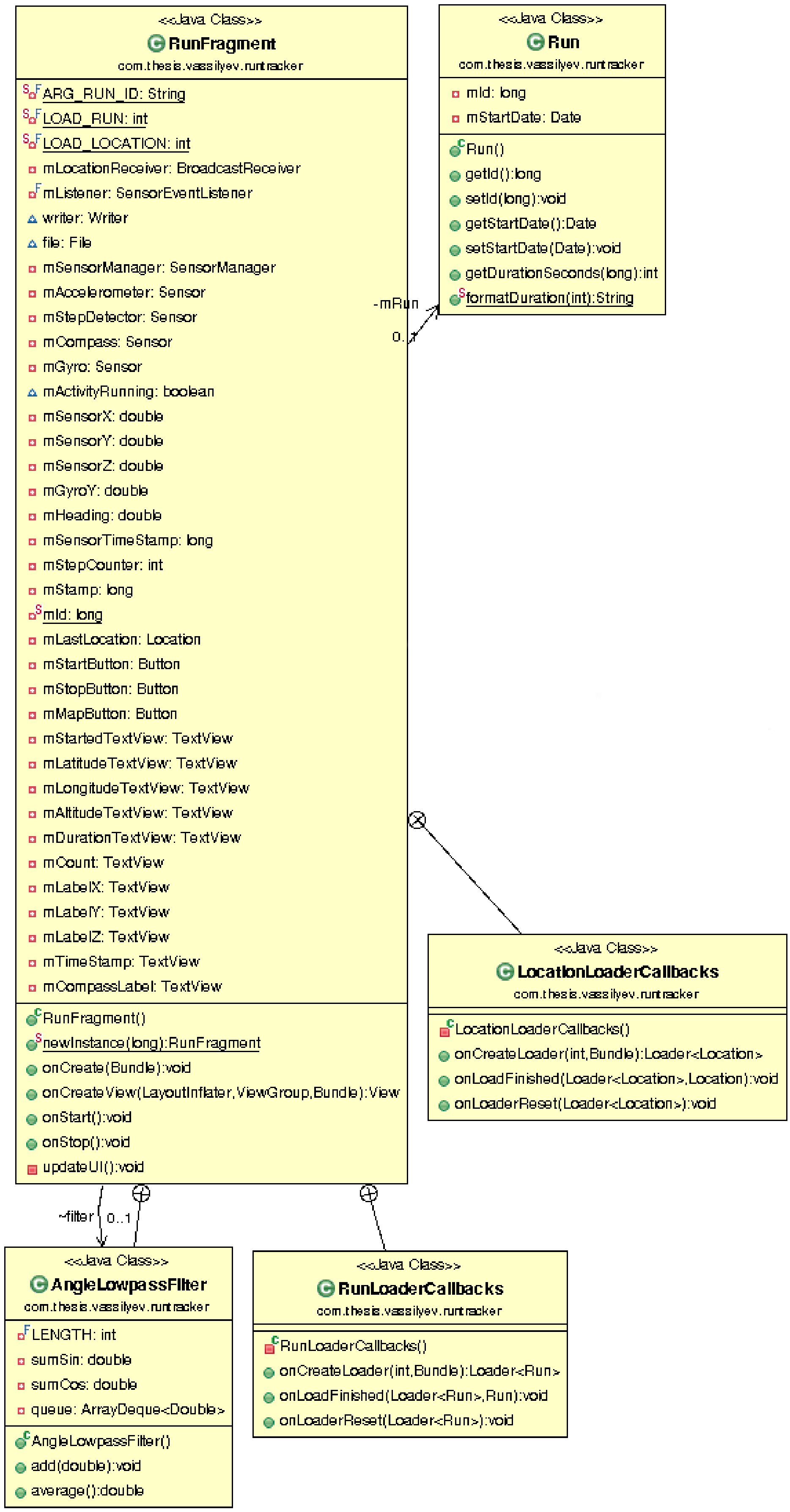
[37] P. H. Dana, “Global Positioning System Overview”, *Department of Geography*, University of Texas in Austin, 1994.

[38] B. W. Carroll, D. A. Ostlie, “An introduction to modern astrophysics. 2nd edition,” Pearson, 2007.

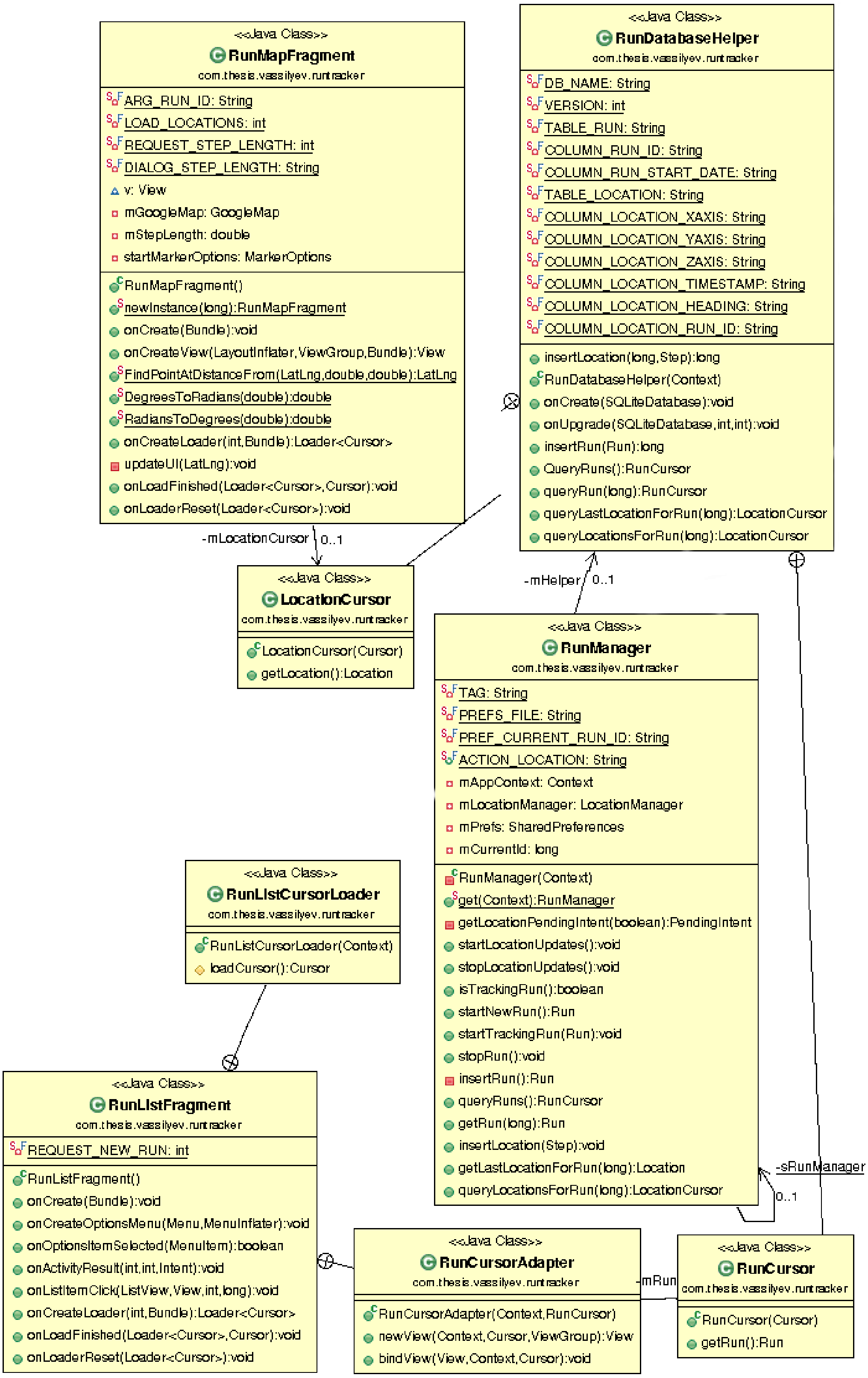
[39] A. S. Pospelov, “Indoor Dead Reckoning,” St.-Petersburg State University of Service and Economy, 2013

[40] IndoorAtlas knowledge base [WWW] [Accessed on 04.10.2014] Available at: https://indooratlas.uservoice.com/knowledgebase/articles/242897-what-is-the-positioning-accuracy-of-indooratlas.

APPENDIX A: CLASS DIAGRAM



APPENDIX B: CLASS DIAGRAM



APPENDIX C: SMARTPHONES COMPARATIVE TABLE

Smartphone model	The average price	Battery	Positioning	Gyroscope	Accelerometers	Barometer	Step detector/step counter	Magnetometer	Proximity/Ambient Light
LG Google Nexus 4	300 euro	2100 mAh	GPS, A-GPS, Glonass	✓	✓	✓	✗	✓	✓
LG Google Nexus 5	399 euro	2,300 mAh	GPS, A-GPS, Glonass	✓	✓	✓	✓	✓	✓
HTC One M8	700 euro	2,600 mAh	GPS, A-GPS, Glonass	✓	✓	✓	✗	✓	✓